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A review on biomass as a fuel for boilers

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ABSTRACT

Currently, fossil fuels such as oil, coal and natural gas represent the prime energy sources in the world. However, it is anticipated that these sources of energy will deplete within the next 40–50 years. Moreover, the expected environmental damages such as the global warming, acid rain and urban smog due to the production of emissions from these sources have tempted the world to try to reduce carbon emissions by 80% and shift towards utilizing a variety of renewable energy resources (RES) which are less environmentally harmful such as solar, wind, biomass etc. in a sustainable way. Biomass is one of the earliest sources of energy with very specific properties. In this review, several aspects which are associated with burning biomass in boilers have been investigated such as composition of biomass, estimating the higher heating value of biomass, comparison between biomass and other fuels, combustion of biomass, co-firing of biomass and coal, impacts of biomass, economic and social analysis of biomass, transportation of biomass, densification of biomass, problems of biomass and future of biomass. It has been found that utilizing biomass in boilers offers many economical, social and environmental benefits such as financial net saving, conservation of fossil fuel resources, job opportunities creation and CO_2 and NO_x emissions reduction. However, care should be taken to other environmental impacts of biomass such as land and water resources, soil erosion, loss of biodiversity and deforestation. Fouling, marketing, low heating value, storage and collections and handling are all associated problems when burning biomass in boilers. The future of biomass in boilers depends upon the development of the markets for fossil fuels and on policy decisions regarding the biomass market.

Contents

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1. Introduction

Currently, fossil fuels such as oil, coal and natural gas represent the prime energy sources in the world (approximately 80% of the total use of more than 400 EJ per year) as shown in Fig. 1. However, it is anticipated that these sources of energy will be depleted within the next 40–50 years. Moreover, the expected environmental damages such as the global warming, acid rain and urban smog due to the production of emissions from these sources have tempted the world to try to reduce carbon emissions by 80% and shift towards utilizing a variety of renewable energy resources (RES) which are less environmentally harmful such as solar, wind, biomass. . .etc. in a sustainable way [1,2]. The Intergovernmental Panel on Climate Change (IPCC) reported that continued emissions from fossil fuels will lead to a temperature increase of between 1.4 and 5.8 °C over the period from 1990 to 2100 [3]. World energy supplies have been dominated by fossil fuels for decades. Today biomass contributes about 10–15% (or 45 ± 10 EJ) of this demand. On average, in the industrialized countries biomass contributes some 9–14% to the total energy supplies, but in developing countries this is as high as one-fifth to one-third [4]. According to the world energy council projections, if the adequate policy initiatives are provided in 2025, 30% of the direct fuel use and 60% of global electricity supplies would be met by renewable energy sources [1].

The major source of GHG emissions from a boiler system is carbon dioxide (CO_2) from the combustion of fossil fuels in the boiler. Other minor sources of GHGs can include methane (CH_4) from leaks in the natural gas distribution system and CH_4 and nitrous oxide (N_2O) as byproducts of combustion processes [5].

Steam systems are a part of almost every major industrial process today. Thirty-seven percent of the fossil fuel burned in US industry is burned to produce steam. This steam, in turn, is used to heat processes, to concentrate and distill liquids, or is used directly as a feedstock. All of the major industrial energy users devote significant proportions of their fossil fuel consumption to steam production: food processing (57%), pulp and paper (81%), chemicals (42%), petroleum refining (23%), and primary metals (10%). Since industrial systems are very diverse, but often have major steam systems in common, it makes a useful target for energy efficiency measures [6]. Saidur and Mekhilef [7] reported that process heat consumes about 20% of total energy in Malaysia rubber producing industries. Fig. 2 shows process heat energy used in Malaysian rubber industries along with other types of energy use.

Biomass is the name given to any organic matter which is derived from plants. That is plant and animal materials such as wood from forests, crops, seaweed, material left over from agricultural and forestry processes, and organic industrial, human and animal wastes. Biomass is a general term which includes phytomass or plant biomass and zoomass or animal biomass. The sun's energy when intercepted by plants and converted by the process of photosynthesis into chemical energy, is 'fixed' or stored in the form of terrestrial and aquatic vegetation. The vegetation when grazed (used as food) by animals gets converted into zoomass (animal biomass) and excreta. The excreta from terrestrial animals, especially dairy animals, can be used as a source of energy, while the excreta from aquatic animals gets dispersed as it is not possible to collect it and process it for energy production [8] (Fig. 3).

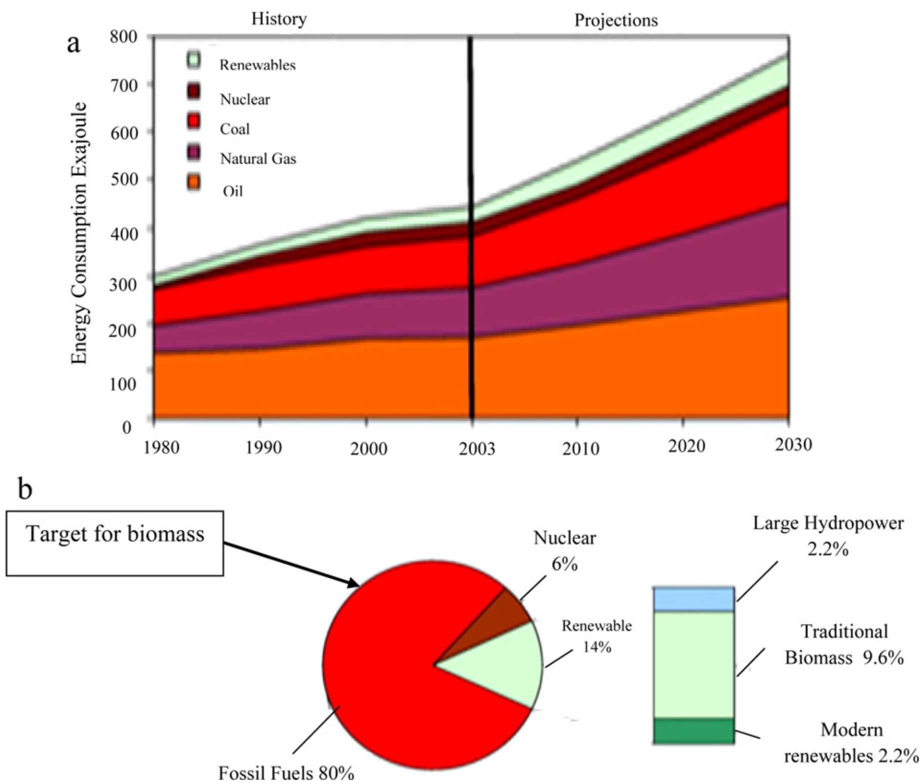


Fig. 1. (a) World marketed energy consumption. (b) Different fuels contribution to total world energy consumption [4].

Biomass is one of the earliest sources of energy especially in rural areas where it is often the only accessible and affordable source of energy [10]. Biomass is made up of carbohydrates. Biomass is a renewable energy source with very specific properties. Compared to other renewable technologies such as solar or wind, biomass has few problems with energy storage; in a sense, biomass is stored energy. Moreover, biomass is a versatile fuel that can produce biogas, liquid fuels and electricity [11]. Sometimes biomass is classified as combustible materials that can be used as an energy source. Biomass is a renewable energy source because its supplies are not limited. We can always grow tress and crops, and waste will always exist [12,13].

The energy contained in biomass originally comes from the sun. Through photosynthesis carbon dioxide in the air is transformed into other carbon containing molecules (e.g. sugars. . .etc.) in plants. These sugars are called carbohydrates and stored in plants and animals or in their waste are called bio-energy (Fig. 4).

Biomass ranks as the fourth source of energy in the world, representing approximately 14% of world final energy consumption, a higher share than that of coal (12%) and comparable to those of gas (15%) and electricity (14%). Biomass is the main source of energy for many developing countries and most of it is noncommercial [8,14].

Biomass sources provide about 3% of all energy consumed in the United States. Biomass supplied about 53% and 47% of all renewable

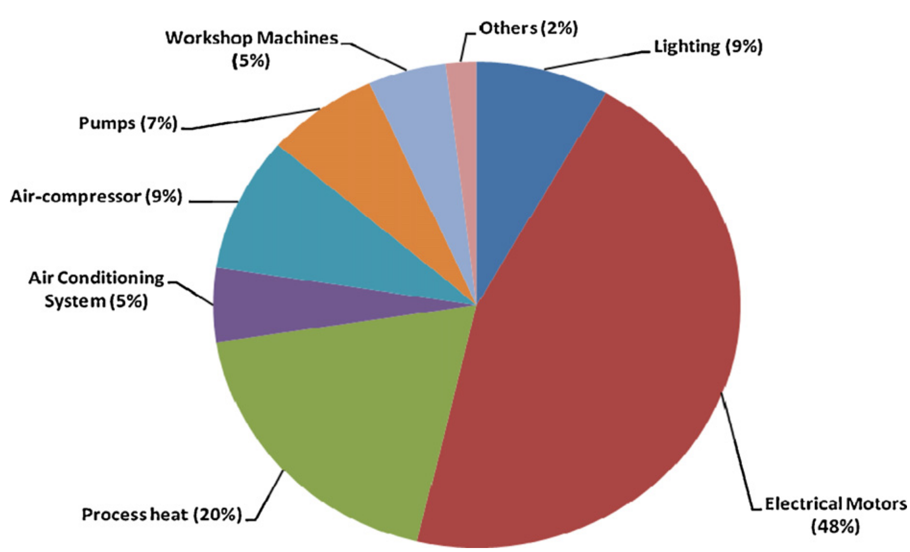


Fig. 2. Energy used by process heat in rubber industries [7].

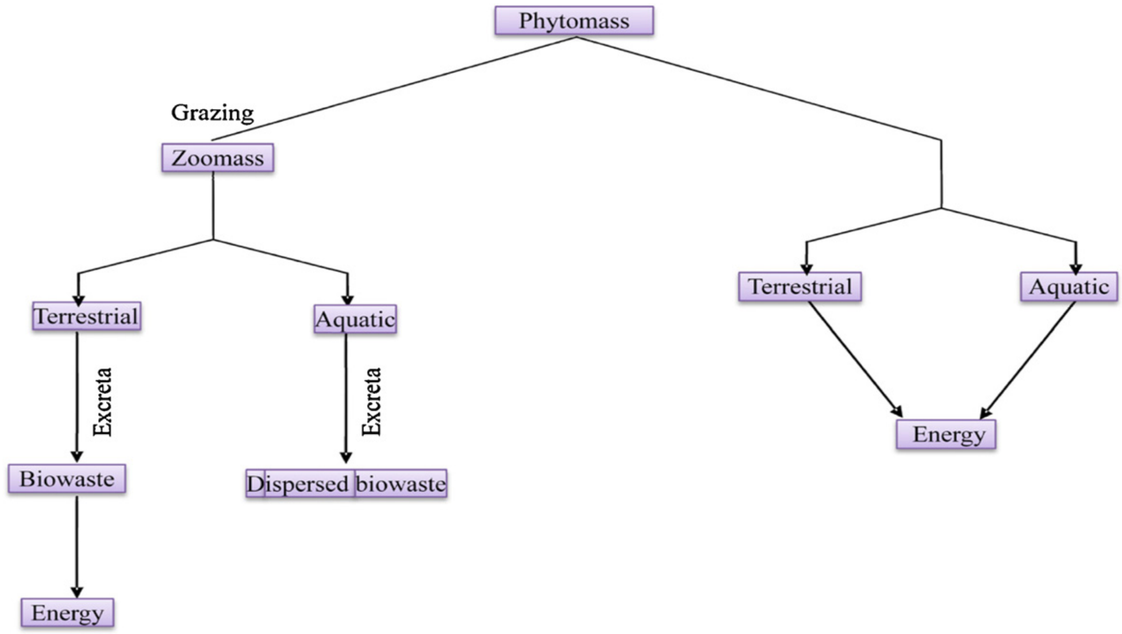


Fig. 3. The solar energy–biomass energy pathways [9].

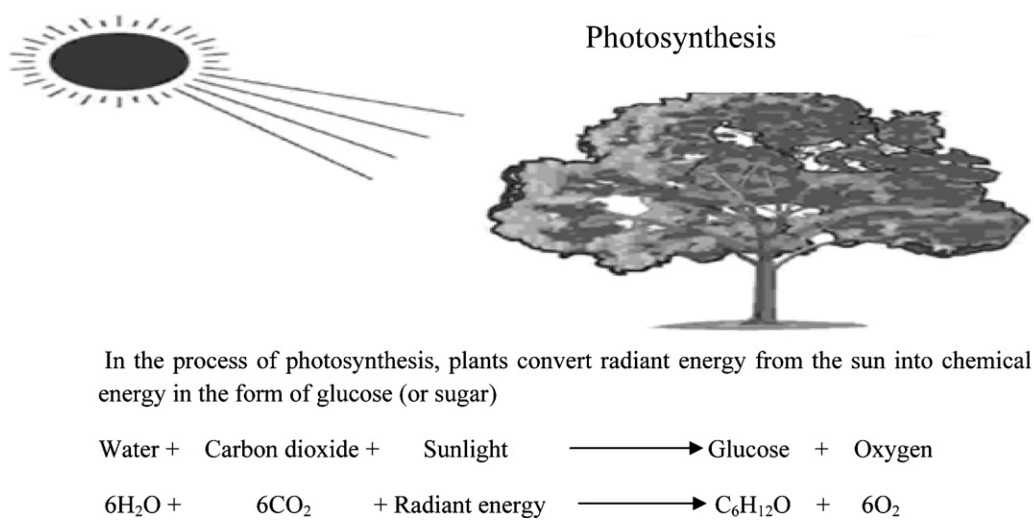


Fig. 4. Source of energy in biomass [13].

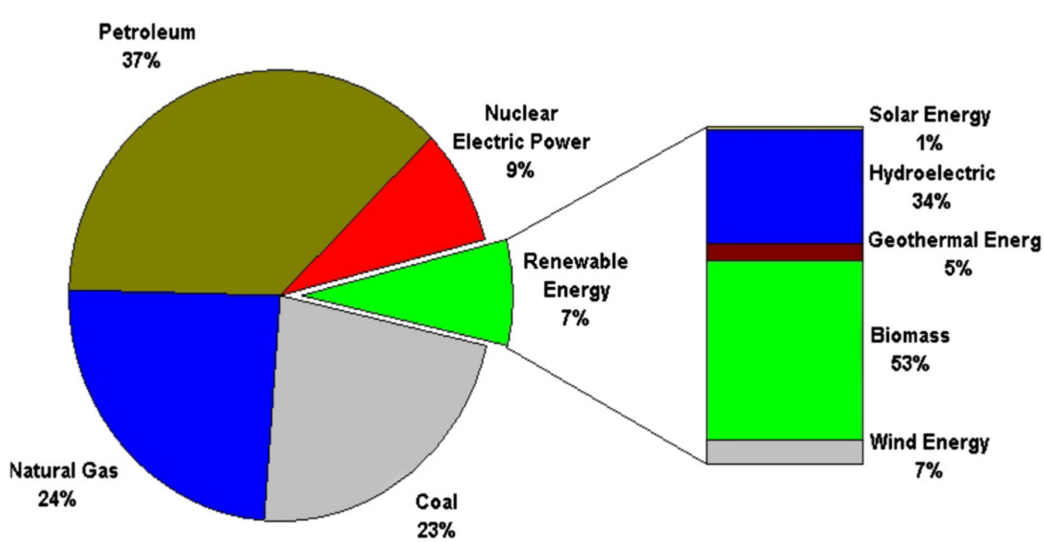


Fig. 5. Consumption of renewable energy in the United States in 2000 [8].

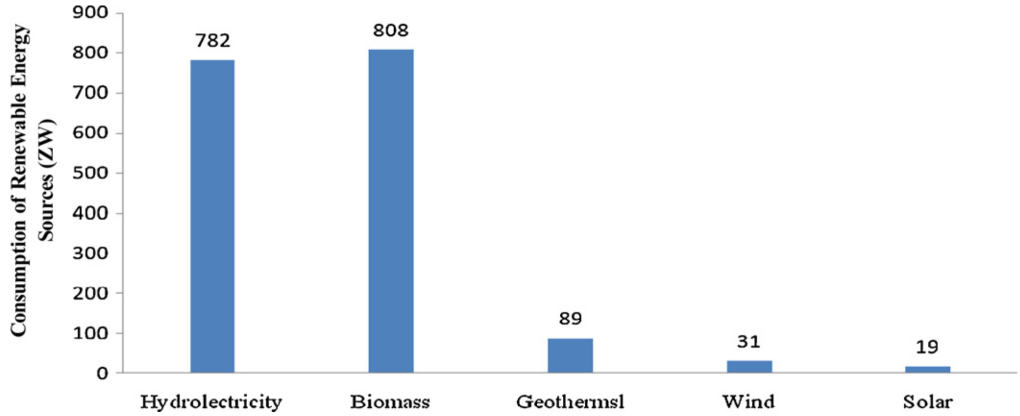


Fig. 6. Consumption of renewable energy sources in the USA in 2002 [8].

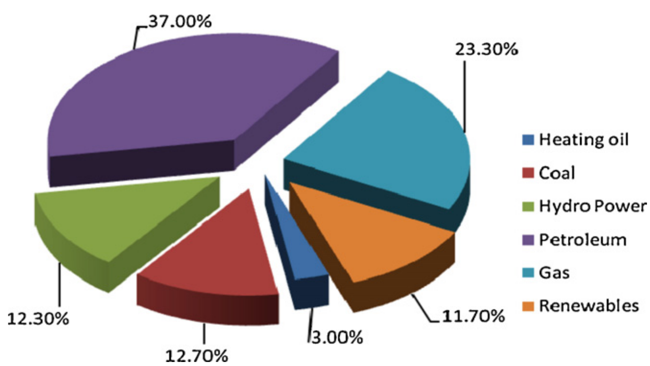


Fig. 7. Energy supply in Austria 2000 [15].

Table 1
The share of biomass in different regions of the world [14].

Region	Share of biomass in final energy consumption (%)
Africa	60.00
South Asia	56.30
East Asia	25.10
China	23.50
Latin America	18.20
Europe	3.50
North America	2.70
Middle East	0.30

energy consumed in the United States in 2000 and 2002 respectively. Biomass supplied almost six times the energy of geothermal, solar and wind energy combined (Figs. 5 and 6) [8].

In 2003 biomass contributed 69 Mtoe (million tons of oil equivalent) to the energy system in European Union (EU25). That is 4% of the total primary energy input. Compared to other renewable heat sources such as solar thermal or geothermal, biomass is still the dominant source: it accounts for 96% of renewable heat [11].

Due to the nature of its natural resources, about 24% of the total energy consumption in Austria is covered by renewable sources of energy. Hydropower, biomass, solar energy and wind energy are promising renewable energy sources for Austria (Fig. 7) [15].

Virtually all countries in South and Southeast Asia are major woodfuel consumers and producers. At present, some 39% of the total energy consumption in the developing countries of the region consists of wood and other biomass fuels, and in absolute terms the consumption is still increasing. Most woodfuels do not originate from natural forests but from agricultural and other land [16]. Table 1 shows the importance of biomass in different world region

1.1. Biomass as a boiler fuel

1.1.1. Characteristics of common industrial fuels

A comparison of industrial fuels must examine the following characteristics of each fuel: (1) cost per BTU as a raw material, (2) availability in any kind of weather and any international political climate; (3) complexity of the on-site equipment need to transport and burn the fuel; (4) problems associated with the storage of the fuel; (5) emissions caused by combustion; and (6) historical success of the technology for boilers using this fuel. Consider coal, fuel oil, and natural gas in the light of these characteristics [17].

1.1.2. Non-conventional fuels

Companies are continually searching for fuels less expensive than coal, fuel oil, and gas. Natural sources such as manufacturing and agricultural waste are inexpensive. Waste materials currently being used as fuels include pulp mill liquor, sawdust, food processing waste, municipal garbage, coal wash water coffee grounds, cardboard, hog fuel (wet bark from plywood operations), and bagasse (sugar cane after the liquid has been extracted). Using industrial wastes as fuels can simplify the disposal process as well as providing an inexpensive source of heat [17].

Still, there are some problems associated with burning any new fuel. The technology for dealing with coal, gas, or fuel oil is well-known. Using a new fuel, however, raises the following questions [17]:

- How high in the combustion chamber should the new fuel be injected into the boiler? (This is critical in burning municipal waste).
- What kind of problems will the ash or residue create?
- What modifications are needed to burners?
- How will the new fuel be transported to and within the facility?
- What storage problems can be expected?
- How regular will the supply be?

2. Biomass as a carbon neutral source of energy

When biomass is burned, or used after converting it to other types of fuel such as solid, liquid, and gaseous fuels (for example charcoal, ethanol, methane), the biomass carbon reacts with oxygen in the air to form carbon dioxide which is released into the atmosphere. If fully combusted the amount of carbon dioxide produced is equal to the amount which was taken from the atmosphere during the growing stage. So there is no net addition of CO_2 and biomass can be regarded as a carbon sink. This is known as the carbon cycle or zero carbon emissions and is illustrated in Fig. 8. In contrast when we burn fossil fuels we make a net addition of CO_2 in

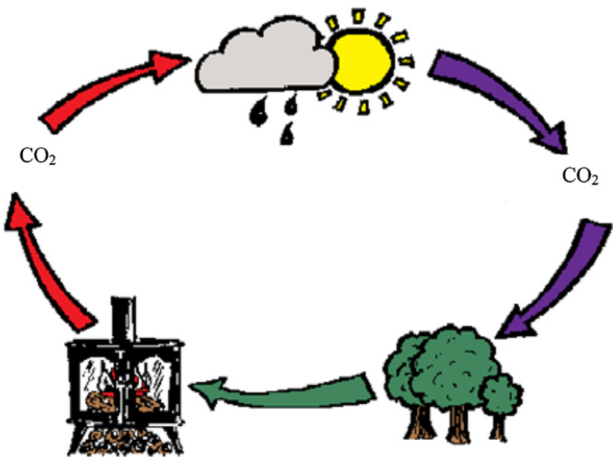


Fig. 8. Carbon cycle [22].

atmosphere. By burning large portions of fossil fuels, this will lead to release enormous quantities of CO_2 within a very short time of about 200 years [9,18–21].

In nature, if biomass is left lying around on the ground it will break down over a long period of time, releasing carbon dioxide and its store of energy slowly. By burning biomass, its store of energy is released quickly and often in a useful way [12].

2.1. Conversion efficiencies of biomass

The yield, the tones of biomass produced per hectare per year, is a very important factor for energy crops. Yields depend on many factors; the location, climate and weather, the nature of the soil, supplies of water, nutrients, etc.. . ., and the choice of plant. Thus, yield implies extremely low conversion efficiency [23].

2.2. Major advantages and disadvantages of biomass fuels

Some of the advantages and disadvantages of biomass are shown in Table 2.

2.3. Sources of biomass

The two main sources of biomass are the purpose-grown energy crops and wastes. Energy crops include woody crops and agricultural crops. Wastes include wood residues, forestry residues; temperate crop wastes, tropical crop wastes, sewage, municipal solid wastes and animal wastes. Some of these sources are shown in Fig. 9 [1,12,19,23,25].

2.4. Composition of biomass

The identification and characterization of chemical and phase compositions of a given solid fuel is the initial and most important step during the investigation and application of such fuel. These compositions are a unique fundamental code that characterizes and determines the properties, quality, potential applications and environmental problems related to any fuel. For that purpose, well-known physical, chemical, petrographic, mineralogical and geochemical studies were used for characterization of solid fuels. Authors used data from: (1) structural analysis, (2) proximate analysis, (3) ultimate analysis, (4) ash analysis, (5) petrographic analysis, (6) mineralogical analysis, (7) separation procedures, and (8) other analyses of fuel, low-temperature ash (LTA) or high-temperature ash (HTA) to characterize specific solid fuels. Identical or similar analyses are also applicable for biomass characterization despite some peculiarities and limitations [24].

2.4.1. Structural composition

Biomass contains varying amounts of cellulose, hemicellulose, lignin and small amounts of lipids, proteins, simple sugars and starches. Biomass also contains inorganic constituents and a fraction of water. Among these compounds, cellulose, hemicellulose, and lignin are the three main constituents [29]. The combination of cellulose, hemicelluloses, and ligninis are called 'lignocellulose', which comprises around half of the plant matter produced by photosynthesis and represents the most abundant renewable organic resource on earth. Cellulose, hemicelluloses and lignin are strongly intermeshed in lignocelluloses and are chemically bonded by non-covalent forces or by covalent crosslinkages.

Cellulose is the largest component of lignocellulosic materials, followed by hemicellulose and lignin. Whereas cellulose and hemicellulose are macromolecules constructed from different sugars; lignin is an aromatic polymer synthesized from phenylpropaniod precursors. The composition and proportions of these compounds in different plants is illustrated in Table 3.

The structural analysis of biomass is particularly important in the development of processes for producing other fuels and chemicals and in the study of combustion phenomenon. Moreover, structural analysis plays an important role in the estimation of the higher heating value of biomass as will be discussed in details in Section 8 [9].

2.4.2. Ultimate compositions

Ultimate analysis is one of the important factors when studying biomass fuels properties. It helps to assess the percentage of N, S and Cl to study the environmental impact of biomass. Moreover, it helps to calculate the percentage of C, H, O to estimate the heating value of these fuels as will be discussed in Section 8. Table 4 shows ultimate analysis of different types of biomass.

2.4.3. Proximate compositions

Proximate analysis helps to assess the percentage of volatile matter, fixed carbon and ash contents. This analysis is very important to study the combustion phenomenon of biomass. For instance, ash contents in biomass fuels can cause ignition and combustion problems. The melting point of the dissolved ash can be low, this causes fouling and slagging problems. High volatility of the biomass offers many advantages as a combustion feedstock. Moreover, high fixed carbon and volatile matter increase the heating value of any biomass fuels. Table 5 shows proximate analysis of different types of biomass.

2.4.3.1. Ash analysis. The composition of biomass ash is strongly dependent on the species and part of the biomass plant. The available nutrients, soil quality, fertilizers and weather conditions have significant impact on the contents of potassium, sodium, chlorine and phosphorus especially in agro-biomass ashes. Ash analysis of different types of biomass is shown in Table 6.

Generally, biomass fuels can be divided into three groups on the basis of their ash composition:

2.4.3.1.1. Biomasses with Ca, K rich and Si lean ash. Generally the ash of woody biomass is typically rich in calcium (Ca) and potassium (K), as shown in Table 7.

2.4.3.1.2. Biomasses with Si rich and Ca, K lean ash. Most fuels in this group belong to herbaceous, or agricultural biofuels. Some of the fuels, like straws of cereals have also relatively high potassium (K) and chlorine (Cl) contents. Rice husk and bagasse have very high SiO_2 contents in ash, see Table 8.

2.4.3.1.3. Biomasses with Ca, K and P rich ash. Sunflower stalk ash and rapeseed expeller ash from food production are examples

Table 2
Major advantages and disadvantages of biomass fuels [20,24–27].

Advantages	Disadvantages
Renewable and inexhaustible fuel source	Incomplete renewable energy resource with respect to the complete life cycle assessment
Commonly low content of ash, C, S, N and trace elements	Miss of accepted terminology, classification systems and standards worldwide
	Commonly high contents of moisture, Cl, K, Na, Mn, and some trace elements
Normally high concentration of volatile matter, CA, H, Mg, O and P	
Great reactivity during conversion	Low energy density
Mitigation of hazardous emissions (CH_4, CO_2, NO_x, SO_x and trace elements and waste separated	Potential competition with food and feed production
Capture of some hazardous components by ash during combustion	
Possible soil damage and loss of biodiversity	
Relatively cheap resource	Odor, potential emission and leaching of hazardous components during disposal and heat treatment
Diversification of fuel supply and energy security	
creation of new jobs	
Potential use of oceans and low-quality soils, and restoration of degraded lands	Great harvesting, collection, transportation, storage cost
Reduction of biomass-containing wastes	Could contribute a great deal to global warming and particulate pollution if directly burned
Can be co-fired with conventional fossil fuels to reduce emissions and achieve economical benefit	
Land used for energy crops maybe in demand for other purposes, such as faming, conservation, housing, resort or agricultural use.	
The use of waste materials reduce landfill disposal and makes more space for everything else.	
Biofuels do not economically compete with conventional (oil, gas, coal) fuels. It costs more to generate electricity from biomass compared to coal	
	Sources of biomass are quite diffuse and may not be available in sufficient quantities to make a national impact as an energy use



Fig. 9. sources of biomass [28]

Table 3
Lignocellulosic constituents of some biomass.

Lignocellulosic residues	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Ash (%)	Reference
Nut shells	25–30	25–30	30–40	NA	[9]
Corn Cobs	35	45	15	1.36	
Paper	0	85–99	0–15	1.1–3.9	
Rice Straw	24	32.1	18	NA	
Sorted Refuse	20	60	20	NA	
Leaves	80–85	15–20	0	NA	
Cotton seeds Hair	5–20	80–95	0	NA	
Waste paper from chemical pulps	10–20	60–70	5–10	NA	
Primary wastewater solids	NA	8–15	24–29	NA	
Sugar cane bagasse	27–32	32–44	19–24	4.5–9	
Barley straw	24–29	31–34	14–15	5–7	
Oat straw	27–38	31–37	16–19	6–8	
Rye straw	27–30	33–35	16–19	2–5	
Bamboo	15–26	26–43	21–31	1.7–5	
Rye grass (early leaf)	15.8	21.3	2.7	NA	
Rye grass (seed setting)	25.7	26.7	7.3	NA	
Orchard grass (medium maturity)	40	32	4.7	NA	
Esparto grass	27–32	33–38	17–19	6–8	
Sabai grass	23.9	NA	22.0	6.0	
Elephant grass	24	22	23.9	6	
Bast fiber seed flax	25	47	23	5	
Bast fiber Kenaf	22–23	31–39	15–19	2–5	
Bast fiber Jute	18–21	45–53	21–26	0.5–2	
Banana waste	14.8	13.2	14	11.4	
Hardwood stems	24–40	40–50	18–25	NA	
Softwood stems	25–35	45–50	25–35	NA	
Beech Wood	31.2	45.3	21.9	NA	[10]
Spruce Wood	20.7	49.8	27.0	NA	
Walnut Shell	22.7	25.6	52.3	NA	
Almond Shell	28.9	50.7	20.4	NA	
Sunflower shell	34.6	48.4	17.0	NA	[30]
Ailanthus wood	26.6	46.7	26.2	NA	
Hazelnut kernel husk	15.7	29.6	53.0	NA	
Corn Cob	32.32	52.49	15.19	NA	[32]
Corn straw	30.88	51.53	17.59	NA	
Olive cake	21.63	23.08	55.29	NA	
Newspaper	25–40	40–55	18–30	NA	[33]
Swine waste	28	6.0	NA	NA	
Solid cattle manure	1.4–3.3	1.6–4.7	2.7–5.7	NA	
Coastal Bermuda grass	35.7	25	6.4	NA	
Grasses	35–50	25–40	10–30	NA	
Hazelnut shell	29.9	25.9	42.5	1.3	
Hazelnut seedcoat	15.7	29.6	53.00	1.40	
Soft Wood	24.4	45.80	28.00	1.7	
Hardwood	31.30	45.30	21.70	2.7	
Waste Material	29.2	50.60	24.70	4.50	
Tea Waste	19.90	30.20	40.00	3.40	
Wood Bark	29.80	24.80	43.80	1.60	
Wheat Straw	39.10	28.80	18.60	13.50	
Corn Stover	30.70	51.20	14.40	3.70	
Tobacco stalk	28.20	42.40	27.00	2.40	
Tobacco Leaf	34.40	36.30	12.10	17.2	
Olive Husk	23.6	24.0	48.4	4.0	
Spruce Wood	21.20	50.80	27.50	0.5	
Beech Wood	31.80	45.80	21.90	0.4	
Ailanthus wood	26.60	46.70	26.20	0.5	
Biomass	20–40	40–60	10–25	NA	[29]
Switchgrass	32.10	37.10	17.20	NA	[34]
Birch wood	25.70	40.00	15.70	NA	[35]
Switch grass	32.10	37.10	17.20	NA	[36]

of the third type of agrobiomass ash, having K_2O, CaO and P_2O_5 as the major ash components as shown in Table 9.

2.5. Biomass conversion routes to energy

Biomass can be converted to fuel by means of numerous processes. The actual choice of a process will depend on the type and quantity of available biomass feedstock, the desired energy carrier(s) (end-use), environmental standards, economic conditions and other factors. For example, biomass can be directly burned as a fuel. However, this manner of use can be regarded as a source of very substantial pollution. Therefore, it is necessary to convert biomass into liquid or gaseous fuels which can replace oil. A large variety of liquid and gaseous fuels can be derived from biomass as shown in Fig. 10 [44].

There are several methods available to convert biomass into useable form of energy. The foremost among them is thermal conversion where combustion, gasification, and pyrolysis are used to retrieve energy from the biomass. The next is biochemical conversion where microorganisms during fermentation, anaero-

Table 4
Ultimate analysis of different types of biomass types (wt% dry basis).

Fuel	C	H	O	N	S	Cl	Ref
Lignite	65.20	4.50	17.50	1.3	4.1	0.40	[37]
Spruce wood	51.40	6.10	41.20	0.3	0.0	0.10	
Hazelnut Shell	50.80	5.60	41.10	1.0	0.0	0.20	
Corncob	49.00	5.40	44.20	0.4	0.0	0.20	
Corn Stover	49.40	5.60	42.50	0.6	0.1	0.30	
Tobacco stalk	49.30	5.60	42.80	0.7	0.0	0.20	
Tobacco leaf	41.20	4.90	33.90	0.9	0.0	0.30	
Almond shell	47.90	6.00	41.70	1.1	006	0.10	
Walnut shell	53.60	6.600	35.50	1.5	0.1	0.20	
Sawdust	46.90	5.20	37.80	0.1	0.04	–	[10]
Rice Husk	47.80	5.10	38.90	0.1	–	–	
Cotton Gin	42.80	5.40	35.00	1.4	0.5	–	
Sugarcane Bagasse	44.80	5.40	39.60	0.4	0.01	–	
Peach Pit	53.00	5.90	39.10	0.3	0.05	–	
Alfafa Stalk	45.40	5.80	36.50	2.1	0.09	–	
Switchgrass	46.70	5.90	37.40	0.8	0.19	–	
Olive Husk	49.90	6.20	42.00	1.6	0.05	0.20	
Beech Wood	49.50	6.20	41.20	0.4	–	–	
Tea Waste	48.00	5.5	44.00	0.5	0.06	0.1	
Sunflower Shell	47.40	5.80	41.3	1.4	0.05	0.1	
Tires	81.5	7.10	3.4	0.5	1.4	–	[19]
Poplar	48.45	5.85	43.69	0.47	0.01	–	
Eucalyptus	48.33	5.89	45.13	0.15	0.01	–	
Red oak wood	50.00	6.00	42.40	0.3	–	–	[31]
Wheat straw	41.80	5.50	35.50	0.7	0.0	1.50	
Alder fill Sawdust	53.20	6.10	4.20	0.50	0.04	0.02	[24]
Balsam bark	54.00	6.20	39.50	0.20	0.10	–	
Beech bark	51.40	6.00	41.80	0.70	0.11	–	
Birch bark	57.00	6.70	35.70	0.50	0.10	–	
Christmas tree	54.50	5.90	38.70	0.50	0.42	–	
Elm bark	50.9	5.80	42.50	0,70	0.11	–	
Olive wood	49.00	5.40	44.90	0.70	0.03		
Pine pruning	51.90	6.30	41.30	0.50	0.01	–	
Spruce bark	53.60	6.20	40.00	0.10	0.10	0.03	
Tamarack bark	57.00	10.20	32.00	0.70	0.11	–	
Willow	49.80	6.10	43.40	0.60	0.06	0.01	
Barley straw	49.40	6.20	43.60	0.70	0.13	0.27	
Sorghastrum grass	49.40	6.30	44.00	0.30	0.05	0.04	
Kenaf grass	48.40	6.00	44.50	1.00	0.15	0.17	
Bamboo whole	52.00	5.10	42.50	0.40	0.04	0.08	
Almond hulls	50.60	6.40	41.70	1.20	0.07	0.02	
Wheat straw	49.40	6.10	43.60	0.70	0.17	0.61	
Coffee husks	45.40	4.90	48.30	1.10	0.35	–	
Cotton husks	50.40	8.40	39.80	1.40	0.01	–	
Palm Kernels	51.00	6.50	39.50	2.70	0.27	0.21	
Pepper residue	45.70	3.20	47.10	3.40	0.60	–	
Plum pits	49.90	6.70	42.40	0.90	0.08	0.01	
Soya husks	45.40	6.70	46.90	0.90	0.10	–	
Chicken litter	60.50	6.80	25.30	6.20	1.20	0.50	
Meat-bone meal	57.30	8.00	20.80	12.20	1,69	0.87	
Mustard husks	45.80	9.20	44.40	0.40	0.20	–	
Sugar cane bagasse	49.80	6.00	43.90	0.20	0.06	0.03	
Walnut hulls and blows	55.10	6.70	36.50	1.60	0.12	0.02	
Coconut shells	51.10	5.60	43.10	0.10	0.10	–	
Sewage sludge	50.90	7.30	33.40	6.10	2.33	0.04	
Wood yard waste	52.20	6.0	40.40	1.1	0.30	0.30	
Pistachio shell	48.79	5.91	43.41	–	–	–	[38]
Wood chips	48.10	5.99	45.72	–	–	–	
Neem wood	48.26	6.27	43.46	–	–	–	
Cereals	46.50	06.10	42.00	01.20	0.10	0.20	[39]
Millet	45.90	05.30	41.10	00.90	0.10	0.30	
Sunflower	50.50	05.90	34.90	01.30	0.10	0.40	
Apricot stones	52.38	06.57	38.78	01.07	0.15	–	[40]
Peach stones	51.35	06.01	40.32	00.58	0.14	–	
Olive cake	46.80	06.07	36.69	00.68	0.12	–	
Switchgrass	42.04	04.97	35.44	0.77	0.18	–	[34]
Rice Straw	38.45	5.28	–	0.88	–	–	[41]

bic digestion and esterification release energy from the biomass. Biochemical conversion is usually preferred for biomass with high water content. The last is the chemical conversion where various chemical reactions draw out energy from the biomass. Fig. 10 shows thermal and biochemical conversion of biomass.

Another technology is represented by mechanical extraction processes, able to produce energy in forms of bio-diesel. However, currently the cost of bio-diesel compared with fossil fuel makes this conversion option strongly uncompetitive, even if an increasing attention of government policies about achievement

Table 5
Proximate analysis of different types of biomass types (wt% dry basis).

Fuel	FC	VM	Ash	Ref
Alfalfa stems	15.81	78.92	05.27	[42]
Wheat straw	17.71	75.27	07.02	
Rice hulls	16.22	63.52	20,26	
Rice straw	15.86	65.47	18.67	
Switch grass	14.34	76.69	08.97	
Sugar cane bagasse	11.95	85.61	02.44	
Willow wood	16.07	82.22	01.71	
Hyprid poplar	12.49	84.81	02.70	
Almond shells	20.71	76.00	03.29	
Almond hulls	20.07	73.80	06.13	
Yard waste	13.59	66.04	20.37	
Fir mill	17.48	82.11	00.41	
Mixed paper	07.42	84.25	08.33	
Rice husk	16.95	61.81	21.24	[38]
Olive husk	26.10	70.30	03.60	
Peanut hull	21.09	73.02	05.89	
Hazelnut shell	28.30	69.30	01.40	
Brazil nut shell	22.20	76.10	01.70	
Akhrot shell	18.78	79.98	01.20	
Coconut shell	22.10	77.19	00.71	
Spruce wood	29.30	70.20	01.50	
Ailanthus wood	24.80	73.50	01.70	
Neem wood	12.19	85.86	01.93	
Douglas fir wood	12.60	87.30	00.10	
Douglas fir bark	32.97	65.46	01.75	
Cotton stalk	19.90	62.90	17.30	
Jawar straw	15.15	75.97	08.88	
Barley straw	13.29	82.41	04.30	
Casurina wood	19.58	78.58	01.83	
Subabul wood	18.52	81.02	01.20	
Sena leaves	25.50	57.20	17.30	
Oak wood	21.90	77.60	00.50	[10]
Beech wood	17.00	82.50	00.50	
Corncob	11.50	87.40	01.10	
Tea waste	13.00	85.50	01.50	
Walnut shell	37.90	59.30	02.80	
Sunflower shell	19.80	76.20	04.00	
Colza seed	15.40	78.10	06.50	
Pine one	21.70	07.30	01.00	
Cotton refuse	12.40	81.00	06.60	
Olive refuse	24.70	66.10	09.20	
Sawdust	15.00	82.20	02.80	
Corn stover	10.90	84.00	05.10	
Birch bark	19.40	78.50	2.10	[24]
Elm bark	18.80	73.10	8.10	
Oak wood	21.40	78.10	0.50	
Willow	15.90	82.50	1.60	
Buffalo gourd grass	13.70	81.60	04.70	
Sorghastrum grass	14.20	81.60	04.20	
Olive pits	19.90	77.00	3.10	
Soya husks	20.30	74.30	5.40	
Coffee husks	20.70	76.50	2.80	
Pine pruning	15.10	82.20	2.70	
Maple bark	19.40	76.60	4.00	
Hemlock bark	25.50	72.00	2.50	
Buffalo gourd grass	13.70	81.6	4.70	
Kenaf grass	17.0	79.4	3.60	
Reed canary grass	17.70	73.4	8.90	
Chicken litter	14.40	47.8	37.80	
Mango wood	11.36	85.64	2.98	[43]
Sudan grass	18.60	72.75	8.65	
Orchard	14.60	83.30	2.10	

of better air-quality standards may rapidly change this situation [45].

2.5.1. Pyrolysis

Pyrolysis of biomass is thermal decomposition of the organic matters in the absence of oxygen. Pyrolysis is a relatively slow chemical reaction occurring at low temperatures to convert biomass to a more useful fuel such as hydrocarbon rich gas mixture and a carbon rich solid residue. The main products of biomass pyrolysis depend on the temperature, heating rate, particle size and catalyst used. Typical gas composition of woody biomass pyrolysis includes CO, CO_2, CH_4 and H_2 as major products along with other organic compounds. Usually, fast pyrolysis yields more gases than solids. The main pyrolysis reaction is: Biomass → Charcoal + Volatile matter (Fig. 11) [14,19,32].

2.5.2. Gasification

Gasification is the thermochemical conversion of biomass into gaseous fuels by means of partial oxidation of the biomass at high temperatures. It can be used to produce a low (4–6 MJ/m^3) to high

Table 6
Ash analysis of different types of biomass.

Fuel	Cl	SiO_2	Al_2O_3	Fe_2O_3	Mn	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3	Reference
Wood pellets	NA	4.30	1.30	1.50	5.90	8.50	55.90	0.60	16.80	0.10	3.90	1.30	[4]
Sunflower pellets	NA	2.90	0.60	0.80	0.10	21.60	21.60	0.24	22.80	0.10	15.20	14.00	
Walnut shell	0.10	23.10	2.40	1.50	NA	13.40	16.60	1.00	32.80	0.10	6.30	2.20	[10]
Almond shell	0.20	23.50	2.70	2.80	NA	5.20	10.50	1.60	48.50	0.10	4.50	0.80	
Olive husk	0.20	32.70	8.40	6.30	NA	4.20	14.50	26.20	4.30	0.30	2.50	0.60	
Hazelnut shell	0.1	33.70	3.10	3.80	NA	7.90	15.40	1.30	30.40	0.10	3.20	1.10	
Rek Oak wood	0.80	49.00	9.50	8.50	NA	1.10	17.50	0.50	9.50	NA	1.80	2.60	[31]
Wheat straw	3.60	48.00	3.50	0.50	NA	1.80	3.70	14.50	20.00	NA	3.50	1.90	
Beech bark	–	12.40	0.12	1.10	–	11.50	68.20	0.90	2.60	0.10	2.30	0.80	[24]
Tamarack bark	–	7.77	8.94	3.83	–	9.04	53.50	3.40	5.64	0.11	5.00	2.77	
Switchgrass	–	66.25	2.22	1.36	–	4.71	10.21	0.58	9.64	0.28	3.92	0.83	
Rice straw	–	77.20	0.55	0.50	–	2.71	2.46	1.79	12.59	0.04	0.98	1.18	
Olive kernel	–	67.7	20.3	0.05	–	0.05	0.5	11.2	0.15	0.05	–	–	[108]

Table 7
Examples of ash compositions of coal, peat, conifer bark and forest residue. Coal and peat were ashed at 815 °C while bark and forest residue at 575 °C.

	Polish coal (wt %)	Peat (wt %)	Bark Conifers (wt %)	Forest residue (wt %)
SiO_2	47.7	32.1	4.8	11.6
Al_2O_2	23.8	17.3	2.8	2.0
Fe_2O_3	9.5	18.8	1.5	1.8
CaO	3.8	15.1	45	40
MgO	2.9	2.5	5.2	4.8
K_2O	2.4	1.4	8.0	9.2
Na_2O	1.1	0.5	0.9	0.6
P_2O_5	0.4	3.7	4.2	4.4
Others	8.4	8.6	27.6	25.6

Table 8
Examples of ash compositions of wheat straw, rice straw, rice husk and bagasse; ashed at 575 °C.

	Wheat straw (wt %)	Rice straw (wt %)	Rice husk (wt %)	Begasse (wt %)
SiO_2	59.9	69.9	95.4	73.0
Al_2O_3	0.8	0.3	0.1	5.0
Fe_2O_3	0.5	0.2	0.1	2.5
CaO	7.3	3.4	0.4	6.2
MgO	1.8	1.6	0.3	2.1
K_2O	16.9	15.3	1.8	3.9
Na_2O	0.4	0.4	0.0	0.3
P_2O_5	2.3	1.5	0.5	1.0
Others	10.1	7.4	1.4	6.0

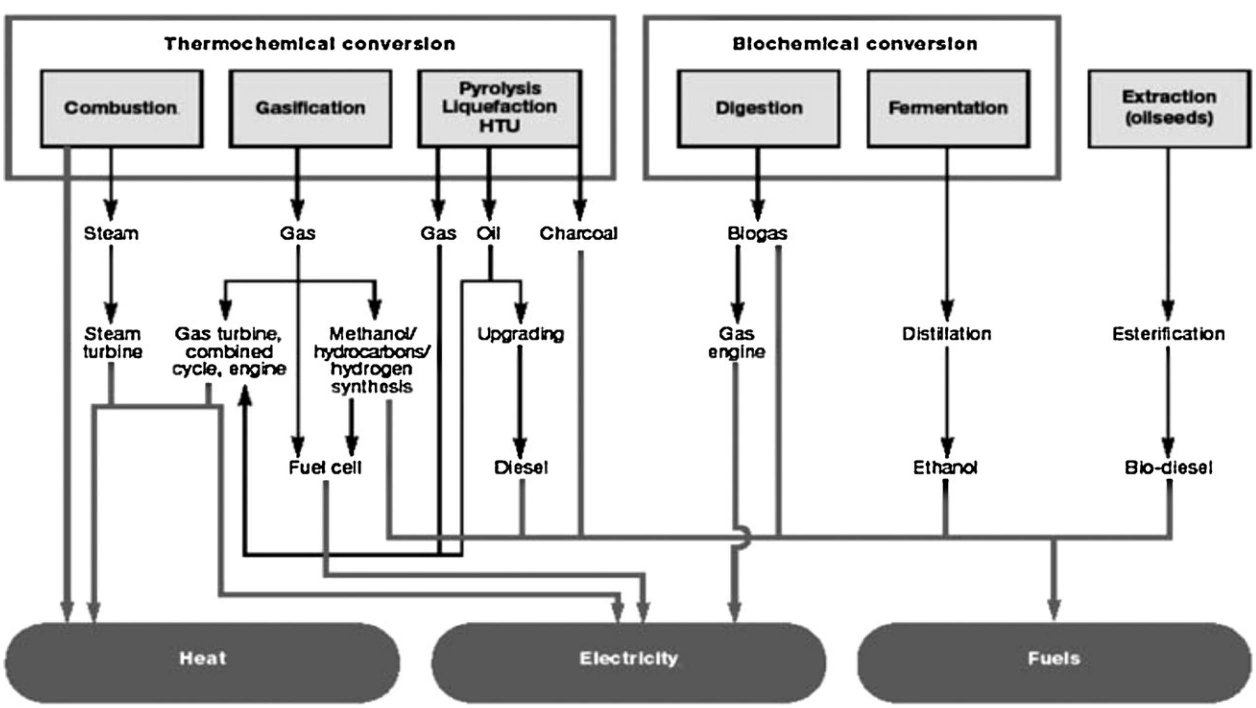


Fig. 10. Main conversion options for biomass to secondary energy carriers [45–47].

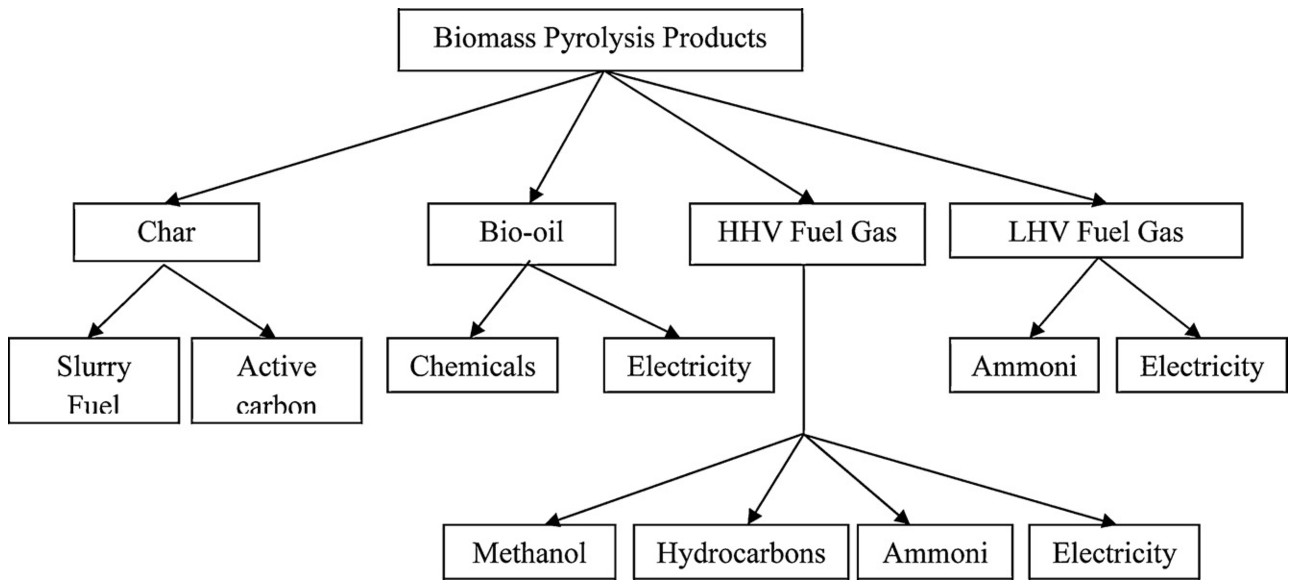


Fig. 11. Fractionation of biomass pyrolysis products [47].

Table 9
Examples of ash compositions of sunflower stalk and rapeseed expeller; ashed at 575 °C.

Elements	Sunflower stalk (wt %)	Rapessed expeller (wt %)
SiO_2	3.1	0.0
Al_2O_2	0.1	0.0
Fe_2O_3	0.2	0.3
CaO	6.6	15.0
MgO	4.3	9.0
K_2O	27.5	22.8
Na_2O	0.0	0.0
P_2O_5	18.5	41.1
Others	39.7	11.8

(4–6 MJ/m^3) caloric value gas. This process also allows for the production of methanol or hydrogen, each of which may have a good future as fuels.

Demirbas [31] shows that the gas produced from biomass in the gasifier typically has a heating value of 300–400 Btu/scf (HHV) and the composition of the gas is as follows:

Hydrogen 30–40%, carbon monoxide 20–30%, methane 10–15%, carbon dioxide 15–20%, ethylene 1%, water 6%, nitrogen 1% [31,44,48].

2.5.3. Direct combustion

Biomass can be burned directly in waste-to-energy plants without any chemicals processing to produce steam for making electricity. Direct combustion and co-firing with coal for electricity production from biomass has been found to be a promising method in the nearest future. Also biomass can be burned to provide heat for industries and homes [14].

2.5.4. Fermentation

Fermentation is the process by which ethanol fuel can be produced. There are several types of process that can produce an alcohol (ethanol) from various plants, especially corn. The two most commonly used processes involve using yeast to ferment the starch in the plant to produce ethanol which can be used as a fuel in the transportation sector. One of the newest processes involves using enzymes to break down the cellulose in the plant's fibers, allowing more ethanol to be made from each plant [13,44,99,100,102,106].

Table 10
HHV correlations and their evaluations.

No.	Correlation (HHV, MJ/kg)	Reference
Based on proximate analysis		
1	HHV = 0.196(FC) + 14.119	[33,49,50]
2	HHV = 0.312(FC) + 0.1534(VM)	
3	HHV = 0.3543(FC) + 0.1798(VM)	
4	HHV = 19.914 − 0.2324Ash	
5	HHV = 14.2 + 0.38(FC) − 9.0721(FC)^2	
Based on structural analysis		
6	HHV = 0.0889(L) + 16.8218	[49]
7	HHV = 0.1739Ce + 0.26631(1 − Ce)	[51]
8	HHV = 0.4373C − 1.6701	[51]
9	HHV = 0.335(C) + 1.423(H) − 0.1540	
10	HHV = 0.335C + 1.423(H) − 0.154(O)0.145(N)	[14]
11	HHV = 0.3516(C) + 1.16225(H) − 0.1109(O) + 0.0628(N) + 0.10465(S)	[52]

2.5.5. Anaerobic digestion

Digestion is the biochemical conversion of organic material to biogas, a mixture of mainly methane and carbon dioxide. The biomass is converted by bacteria in an anaerobic environment in absence of oxygen. Anaerobic digestion is a commercially proven technology and is widely used for treating wet organic wastes. Biogas can be used in many different applications. It can be upgraded to natural gas quality and applied in grids [14,44].

2.5.6. Chemical conversion

Biomass can be converted into gas or liquid fuels by using chemicals or heat. In India cow manure is converted to methane gas to produce electricity. Methane gas can be converted to methanol, a liquid form of methane [12,13].

2.6. Estimating the higher heating value of biomass

There are so many correlations available in the literature to calculate higher heating value of biomass. In this paper the correlations are combined into three groups according to the approaches used; estimating the HHV based on the proximate, ultimate and structural analysis ten correlations proposed and/or applied for estimating the biomass HHV were collected from the literature and shown in Table 10.

Table 11
Relationship between Lignin contents and energy contents of different biomass fuels.

Type of biomass	Lignin	Energy contents (MJ/kg)	Source
Tobacco leaf	15.01	17.97	[32]
Corn cob	15.19	17.99	
Corn straw	17.59	18.20	
Wheat straw	20.98	18.51	
Waste materialy	24.37	18.81	
Beech wood	21.87	18.58	
Hardwood	21.89	18.59	
Ailanthus wood	25.75	18.93	
Tobacco stalk	26.79	19.02	
Softwood	32.55	19.53	
Spruce wood	31.58	19.45	
Hazelnut shell	43.01	20.47	
Wood bark	44.13	20.57	
Olive cake	55.29	21.57	

The lignin content of the lignocellulosic fuel generally is strongly correlated with the heating value. The high heating values of lignin are reported to be higher than the cellulose and hemicellulose. The latter has a lower heating value due to its higher degree of oxidation (Table 11).

The heating value, also called calorific value, of the biomass can be defined by the higher heating value (HHV), which is basically the energy content on a dry basis. The lower heating value (LHV) is calculated by subtracting the energy needed to evaporate the moisture content of the fuel. C and H tend to raise the heating value while oxygen decreases it [4]. Table 12 shows some energy contents of different biomass fuels.

2.7. Comparison between biomass and other fuels

Biomass differs from coal in many important ways, including the organic, inorganic and energy content and physical properties. Relative to coal, biomass generally has less carbon, more oxygen, higher hydrogen content and larger volatile component, more silica and potassium, less aluminum and sometimes calcium, titanium and iron and lower heating value (Tables 13 and 14). Generally, biomass fuels behave similarly to low-rank coals [19,55].

Other notable properties of biomass relative to coal are high moisture; volatile and ash content as shown in Table 15.

Zhang et al. [29] shows the difference between bio-fuel and heavy fuel oil as shown in Table 16.

As compared to deposits from coal combustion, the tenacity and the strength of the biomass combustion deposits will be higher, with smooth deposit surfaces and little deposit porosity. This means that the deposits from biomass combustion may be hard to remove and may require additional cleaning effort [19].

In comparison to gaseous and liquid fossil fuels, the emissions of particulate matter from biomass are higher, leading to concerns about the availability of cost-effective techniques to reduce aerosol emissions in small scale biomass combustion plants [57].

The ignition process of biomass is similar to that for coal except there is more VM available for reaction in a biomass fuel. It is, therefore, more likely that homogeneous ignition will occur for biomass fuels [19].

2.7.1. Summary comparison of coal and biomass combustion

A comparison of pyrolysis, ignition and combustion of coal and biomass particles are shown in Table 17.

2.8. Combustion of biomass

Generally, combustion is a complex phenomenon which involves simultaneous coupled heat and mass transfer with chem-

Table 12
Typical energy contents of different types of biomass.

Type of biomass	Energy contents (MJ/kg)	Source
Green wood	8	[12]
Oven dry plant matter	20	
Methane gas	55	
Almond shell	19.8	[14]
Almond hulls	20	
Beech wood	19.6	
Hazelnut shell	19.5	
Oak wood	19.8	
Oak bark	22	
Olive pits	22	
Olive husk	21.8	
Pistachio shells	19.9	
Rice straw	18.7	
Spruce wood	20.5	
Switcgrass	19.9	
Wheat straw	19.3	
Apricot stones	22.082	[40]
Peach stones	20.657	
Olive cake	19.813	
Tuncbilek lignite	23.212	
Hazelnut Seedcoat	19.2	[19]
Olive Husk	18.8	
Softwoods	19.8	
Hardwoods	19.0	
Wood Bark	20.3	
Waste Material	17.2	
Corncob	17.3	
Tea waste	17.2	
Pine Sawdust	18.142	
Wood	17.742	
Manure	8.650	
Switchgrass	15.997	
Straw	17.090	
Sewage	10.510	
Corn Stover	10.730	
Cotton Gin	15.500	
Coconut Shell	20.00	
Rice Husk	13.524	
Mustard Stalk	10.73	
Barely Straw	17.31	
Peat	15.30	
Fuelwood	16.10	
Sawdust	18.14	
Redwood	20.72	
Tan oak	18.93	
Black locust	19.71	
Tires	36.800	
Municipal solid Waste	15.95–17.533	
Poplar	19.38	
Eucalyptus (Grandis)	19.35	
Colza seed	19.38	[37]
Pine cone	18.65	
Cotton refuse	18.83	
Olive refuse	15.77	
Sugar beet	17.40	[53]
Potatoes	17.00	
Rape seed	27.80	
Lucerne	19.0	
Cereals	18.61	[39]
Millet	18.165	
Sunflower	20.262	
Cotton cake	17.50	[50]
Soybean cake	18.30	
Peanut shell	18.46	
Potato peel	17.18	
Peach bagasse	16.24	
Sourcheery stalk	17.59	
Coir pith	19.50	[54]
Groundnut shell	19.80	

Table 13
Physical, chemical and fuel properties of biomass and coal fuels.

Property	Biomass	Coal	Reference
Fuel density	500	1300	[10]
Particle size (mm)	3	100	
C content (wet % of dry fuel)	43–54	65–85	
O content (wet % of dry fuel)	35–45	2–15	
S content (wet % of dry fuel)	Max 0.5	0.5–7.5	
SiO_2content (wet % of dry fuel)	23–49	40–60	
K_2Ocontent (wet % of dry fuel)	4–48	2–6	
AL_2O_3 content (wet % of dry fuel)	2.4–9.5	15–25	
Fe_2O_3content (wet % of dry fuel)	1.5–8.5	8–18	
Ignition temperature	418–426	490–595	
Heating value	14–21	23–28	

ical reaction and fluid flow. The prediction of combustion for the purposes of design requires knowledge of fuel properties and compositions and the manner in which these factors might influence the outcome of the combustion process. It has been found that, biomass materials show different combustion characteristics according to their elemental composition. Biomass combustion is a series of chemical reactions by which mainly carbon is oxidized to carbon dioxide, and hydrogen is oxidized to water. However, there are many elements that go into the combustion. Reaction for the combustion of a biomass fuel in air might take the following form, where the first reactant compound is a biomass fuel.

$$\begin{aligned}&C_{x1}H_{x2}O_{x3}N_{x4}S_{x5}Cl_{x6}Si_{x7}K_{x8}Ca_{x9}Mg_{x10}Na_{x11}P_{x12}Fe_{x13}Al_{x14}Ti_{x15}\\&+nH_2O+n_2(1+e)(O_2+3.76N_2)=n_3CO_2+n_4H_2O\\&+n_5O_2+n_6N_2+n_7CO+n_8CH_4+n_9NO+n_{10}NO_2+n_{11}SO_2\\&+n_{12}HCl+n_{13}KCl+n_{14}K_2SO_4+n_{15}C+\cdots+\text{Energy}\end{aligned}$$

The inclusion of 15 elements in the empirical formula for the fuel is incomplete. There are many more, especially with respect to inorganic constituents which are very important to the issue of biomass combustion and associated problems such as fouling and slagging. The second reactant term expresses the moisture in the fuel. If too much moisture is present, the fuel will not spontaneously react. The third term represents air and is represented by the simple binary mixture of oxygen and nitrogen in the volume ratio of 21–79%. The product side of the reaction is complex. The main products are those appearing first, but there are other products which are produced during combustion such as CO, hydrocarbons HC, oxides of nitrogen and sulfur as well as the inorganic species such as the alkali chlorides, sulfates, carbonates and silicates [14,42].

Fuel properties for the combustion analysis of biomass fuels can be conveniently grouped into physical, chemical, thermal, and mineral properties.

Table 16
Typical properties of wood pyrolysis bio-oil and of heavy fuel oil [29].

Physical property	Bio-oil	Heavy fuel oil
Moisture Content (wt %)	15–30	0.10
pH	2.50	–
Specific gravity	1.20	0.94
Elemental composition		
C	54–58	85
H	5.5–7.0	11
O	35–40	1.0
N	0–0.2	0.30
Ash	0–0.2	0.10
HHV (MJ/kg)	16–19	40
Viscosity (at 50 °C)	40–100	180
Solids (wt%)	0.2–1	1
Distillation residue (wt%)	Up to 50	1

Table 17
Comparative properties of biomass and coal [19].

Properties	Comparison
Pyrolysis	Starts earlier for biomass fuels compared to coal fuels and releases CO, CO_2 and H_2O
Volatile matter	Higher in biomass compared to that of coal.
Heating value volatiles	Specific heating value of volatiles in kJ per kg is lower for biomass fuels compared to those from coal fuel.
Heat contribution by volatiles	The fractional heat contribution by volatiles in biomass is of the order of, 70% compared to,36% for coal
Oxygen contents	Biomass char has more oxygen compared to coal.
Ash contents	Biomass fuels have ash that is more alkaline in nature, which may exaggerate the fouling problems

Physical properties include density; porosity, particle size, and shape distribution are related to fuel preparation methods. Important chemical properties for combustion are the elemental analysis, proximate analysis, higher heating value. Thermal property values such as specific heat, thermal conductivity, and emissivity vary with moisture content, temperature, and degree of thermal degradation by one order of magnitude [14].

Biomass offers important advantages as a combustion feedstock because of the high volatility of the fuel and the high reactivity of both the fuel and the resulting char [14].

Isothermal and non-isothermal thermogravimetric techniques have commonly been used to investigate the reactivities of carbonaceous materials. A plot of the rate of weight loss against temperature while burning a sample under an oxidizing atmosphere is referred to as the "burning profile". The burning profiles of the biomass samples are shown in Figs. 12–16. The first peak

Table 14
properties of coal and different biomass fuels [56].

Fuel name	Coal	Swedish wood	Straw	Palm kernels	Wood pellets	High-protein biomass
Inherent moisture (%)	4.38	9.53	8.31	9.3	5.43	1.95
Ash content (%)	12.12	1.82	14.24	4.24	2.55	27.88
Volatile content (%)	32.50	81.32	72.00	71.63	79.16	79.12
Carbon content (%)	68.80	44.97	38.46	44.20	47.91	40.73
Gross calorific value (kJ/kg)	27443.5	17210.5	15353.5	18719.0	18710.5	17449.5
Bulk density (kg/m^3)	1300	500	500	500	500	NA

Table 15
Moisture, volatile and ash content of coal and biomass fuels.

Fuel	Moisture (% of fuel)	Ash (% of fuel)	Volatile matter (% of fuel)	Reference
Coal	4.8 ± 2.6	8.3 ± 1.5	2.4 ± 5.9	[31]
Oak wood	6.5 ± 0.8	0.5 ± 0.1	78.6 ± 3.8	
Wheat straw	7.3 ± 1	12.7 ± 3.6	64.0 ± 5.1	

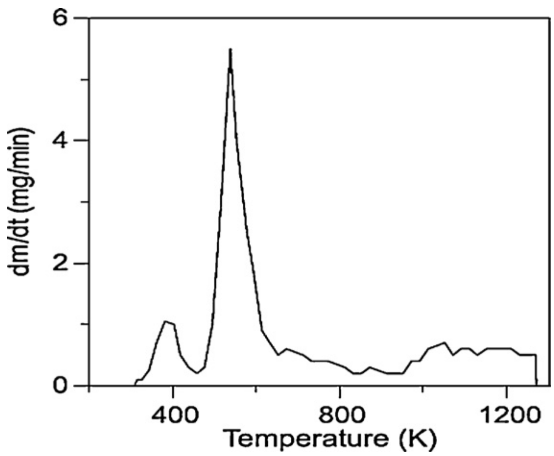


Fig. 12. Burning profile of sunflower shell [10].

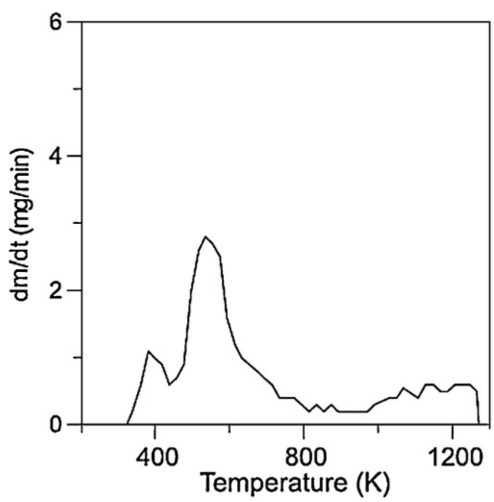


Fig. 13. Burning profile of colza seed [10].

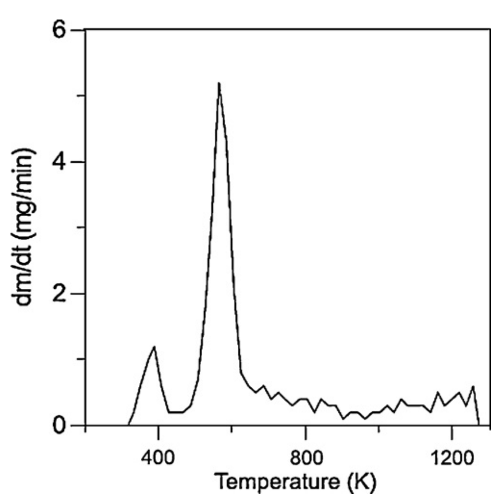


Fig. 14. Burning profile of pine cone [10].

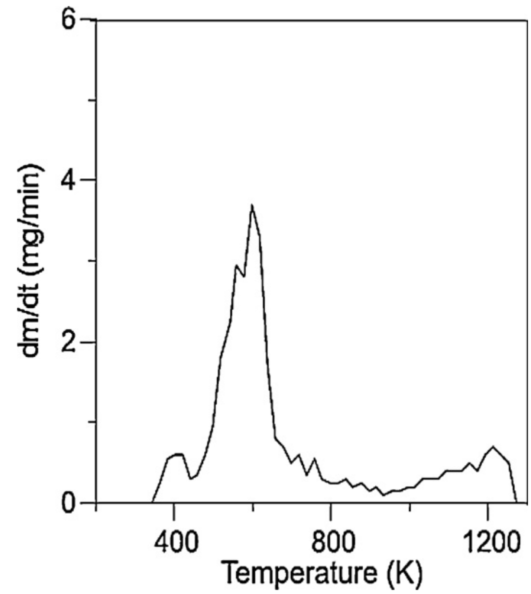


Fig. 15. Burning profile of cotton refuse [10].

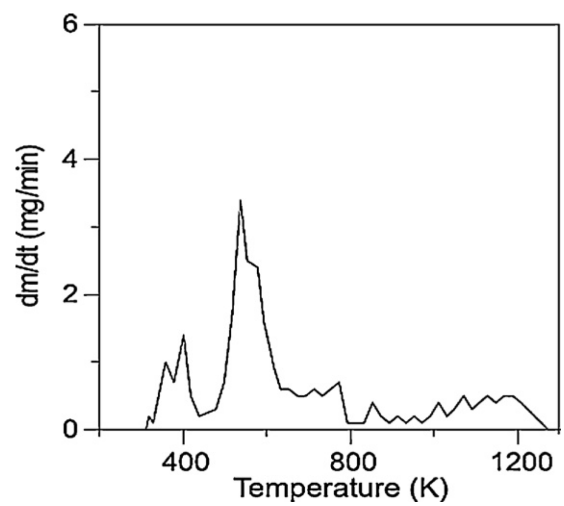


Fig. 16. Burning profile of olive refuse [10].

observed on the burning profiles of the biomass samples corresponds to their moisture release. After releasing the moisture, some small losses in the mass of the sample occurred due to desorption of the adsorbed gases. A sudden loss in the mass of the samples started at the temperature between 450 and 500 K, representing the release of some volatiles and their ignition. In the rapid burning region, the rate of mass loss proceeded so rapidly that it reached its maximum value. The rapid loss of mass immediately slowed at temperatures between 600 and 700 K. After this point, the burning rate apparently decreased, and consequently, some small losses in the mass of the sample continued as long as the temperature was increased up to 1273 K, indicating slow burning of the partly carbonized residue. At the end of the hold time at 1273 K, the samples reached constant weight after given periods. These periods were determined as 5 min for sunflower shell, 7.5 min for colza seed, 18 min for pine cone, 10 min for cotton refuse and 8.5 min for olive refuse.

The most important characteristic temperatures of a burning profile are 'ignition temperature and 'peak temperature'. The ignition temperature corresponds to the point at which the burning profile underwent a sudden rise. The ignition temperatures of the samples were determined from their burning profiles. These temperatures were determined as 475 K for sunflower shell, 423 K for colza seed, 475 K for pine cone, 423 K for cotton refuse and 473 K for olive refuse. It can be concluded that although the proximate analysis results differ considerably, the ignition temperatures of the biomass samples changed in a narrow interval. The point on the burning profile at which the rate of weight loss due to combus-

Table 18
Combustion properties of biomass samples [10,37].

Sample	Ignition temperature (K)	Maximum combustion rate (mg/min)	Peak temperature (K)
Sunflower	475	5.50	573
Colza seed	423	2.80	535
Pine cone	475	5.20	565
Cotton refuse	423	3.70	598
Olive refuse	473	3.40	537

tion is maximum is called 'peak temperature'. The burning profile peak temperature is usually taken as a measure of the reactivity of the sample. These temperatures were found as 573 K for sunflower shell, 535 K for colza seed, 565 K for pine cone, 598 K for cotton refuses and 537 K for olive refuse. It has been observed that an increase in the volatile matter content of the biomass sample causes an increase in the peak temperature.

The rate of weight loss at the burning profile peak temperature is called the 'maximum combustion rate'. The maximum combustion rates of the sunflower shell, colza seed, pine cone, cotton refuse and olive refuse were calculated as 5.5, 2.8, 5.2, 3.7 and 3.4 mg/min, respectively (Table 18). The difference between the maximum combustion rates of the samples can be attributed to the differences in their chemical and physical properties [10,37].

2.8.1. Combustion technology for boilers

There are many combustion technologies available for biomass combustion such as: fixed bed combustion, fluidized bed combustion and pulverized bed combustion. Fluidized bed combustion is the best technology used to burn a fuel with low quality, high ash content and low calorific value. The other firing systems have got limitations and are techno-economically unviable to meet the challenges of biomass fuel properties [58,95].

Fluidized bed combustion has emerged as a viable alternative and has significant advantages over conventional firing system and offers multiple benefits such as compact boiler design, fuel flexibility, higher combustion efficiency and reduced emission of noxious pollutants such as SO_x and NO_x. The fuels burnt in these boilers include coal and biomass. The fluidized bed boilers have a wide capacity range 0.5 T/h to over 100 T/h.

2.8.1.1. Types of fluidized bed combustion boilers. There are three basic types of fluidized bed combustion boilers:

a. Atmospheric classic fluidized bed combustion system (AFBC).
b. Atmospheric circulating (fast) fluidized bed combustion system (CFBC).
c. Pressurized fluidized bed combustion System (PFBC).

2.8.1.1.1. AFBC/bubbling bed. In AFBC, fuel is crushed to a size of 1–10 mm depending on the rank of fuel, type of fuel feed and fed into the combustion chamber. The atmospheric air, which acts as both the fluidization air and combustion air, is delivered at a pressure and flows through the bed after being preheated by the exhaust flue gases. The velocity of fluidizing air is in the range of 1.2–3.7 m/s. The rate at which air is blown through the bed determines the amount of fuel that can be reacted.

2.8.1.1.1.1. Features of bubbling bed boiler:. Fluidized bed boiler can operate at near atmospheric or elevated pressure and have these a-essential features:

- Distribution plate through which air is blown for fluidizing.
- Immersed steam-raising or water heating tubes which extract heat directly from the bed.
- Tubes above the bed which extract heat from hot combustion gas before it enters the flue duct.

2.8.1.1.1.2. General arrangements of AFBC boiler. AFBC boilers comprise of following systems:

i). Fuel feeding system
ii). Air Distributor
iii). Bed and In-bed heat transfer surface
iv). Ash handling system.

2.8.1.1.2. Circulating fluidized bed combustion (CFBC). Circulating fluidized bed combustion (CFBC) technology has evolved from conventional bubbling bed combustion as a means to overcome some of the drawbacks associated with conventional bubbling bed combustion.

This CFBC technology utilizes the fluidized bed principle in which crushed (6–12 mm size) fuel and limestone are injected into the furnace or combustor. The particles are suspended in a stream of upwardly flowing air (60–70% of the total air), which enters the bottom of the furnace through air distribution nozzles. The fluidizing velocity in circulating beds ranges from 3.7 to 9 m/s. The balance of combustion air is admitted above the bottom of the furnace as secondary air. The combustion takes place at 840–900 °C, and the fine particles (<450 microns) are elutriated out of the furnace with flue gas velocity of 4–6 m/s. The particles are then collected by the solids separators and circulated back into the furnace, these solids are about 50–100 kg per kg of fuel burnt.

A CFBC could be good choice if the following conditions are met.

- Capacity of boiler is large to medium
- Sulfur emission and NO_x control is important
- The boiler is required to fire low-grade fuel or fuel with highly fluctuating fuel quality.

Features of the circulating bed system:

Major performance features of the circulating bed system are as follows:

a) It has a high processing capacity because of the high gas velocity through the system.
b) The temperature of about 870 °C is reasonably constant throughout the process because of the high turbulence and circulation of solids. The low combustion temperature also results in minimal NO_x formation.
c) Sulfur present in the fuel is retained in the circulating solids in the form of calcium sulphate and removed in solid form. The use of limestone or dolomite sorbents allows a higher sulfur retention rate, and limestone requirements have been demonstrated to be substantially less than with bubbling bed combustor.
d) The combustion air is supplied at 1.5–2 psig rather than 3–5 psig as required by bubbling bed combustors.
e) It has high combustion efficiency.
f) It has a better turndown ratio than bubbling bed systems.
g) Erosion of the heat transfer surface in the combustion chamber is reduced, since the surface is parallel to the flow. In a bubbling bed system, the surface generally is perpendicular to the flow.

2.8.1.1.3. Pressurized fluid bed combustion. Pressurized fluid bed combustion (PFBC) is a variation of fluid bed technology that is meant for large-scale coal burning applications. In PFBC, the bed vessel is operated at pressure up to 16 kg/cm^2.

2.8.1.2. Advantages of fluidized bed combustion boilers.

i). High Efficiency
FBC boilers can burn fuel with a combustion efficiency of over 95% irrespective of ash content. FBC boilers can operate with overall efficiency of 84% (±2%).

ii). Reduction in boiler size.
High heat transfer rate over a small heat transfer area immersed in the bed result in overall size reduction of the boiler.

iii). Fuel flexibility
FBC boilers can be operated efficiently with a variety of fuels. Even fuels like flotation slimes, washer rejects, agro waste can be burnt efficiently. These can be fed either independently or in combination with coal into the same furnace.

iv). Ability to burn low grade fuel
FBC boilers would give the rated output even with inferior quality fuel. The boilers can fire coals with ash content as high as 62% and having calorific value as low as 2500 kcal/kg. Even carbon content of only 1% by weight can sustain the fluidized bed combustion.

v). Ability to Burn Fines
Coal containing fines below 6 mm can be burnt efficiently in FBC boiler, which is very difficult to achieve in conventional firing system.

vi). Pollution Control
SO_2 formation can be greatly minimized by addition of limestone or dolomite for high sulfur coals. 3% limestone is required for every 1% sulfur in the coal feed. Low combustion temperature eliminates NO_x formation.

vii). Low Corrosion and Erosion
The corrosion and erosion effects are less due to lower combustion temperature, softness of ash and low particle velocity (of the order of 1 m/s).

viii). Easier ash removal – no clinker formation
Since the temperature of the furnace is in the range of 750–900 °C in FBC boilers, even coal of low ash fusion temperature can be burnt without clinker formation. Ash removal is easier as the ash flows like liquid from the combustion chamber. Hence less manpower is required for ash handling.

ix). Less excess air–higher CO_2 in flue gas
The CO_2 in the flue gases will be of the order of 14–15% at full load. Hence, the FBC boiler can operate at low excess air – only 20–25%.

x). Simple operation, quick start-up
High turbulence of the bed facilitates quick start up and shut down. Full automation of start up and operation using reliable equipment is possible.

xi). Fast response to load fluctuations inherent high thermal storage characteristics can easily absorb fluctuation in fuel feed rates. Response to changing load is comparable to that of oil fired boilers.

xii). No Slagging in the Furnace-No Soot Blowing
In FBC boilers, volatilization of alkali components in ash does not take place and the ash is non sticky. This means that there is no slagging or soot blowing.

xiii). Provisions of automatic coal and ash handling system
Automatic systems for coal and ash handling can be incorporated, making the plant easy to operate comparable to oil or gas fired installation.

xiv). Provision of automatic ignition system
Control systems using micro-processors and automatic ignition equipment give excellent control with minimum manual supervision.

xv). High reliability
The absence of moving parts in the combustion zone results in a high degree of reliability and low maintenance costs.

xvi). Reduced Maintenance
Routine overhauls are infrequent and high efficiency is maintained for long periods.

xvii). Quick responses to changing demand
A fluidized bed combustor can respond to changing heat demands more easily than stoker fired systems. This makes it very suitable for applications such as thermal fluid heaters, which require rapid responses.

xviii). High efficiency of power generation
By operating the fluidized bed at elevated pressure, it can be used to generate hot pressurized gases to power a gas turbine. This can be combined with a conventional steam turbine to improve the efficiency of electricity generation and give a potential fuel savings of at least 4% [58].

2.9. Co-firing of biomass and coal

Co-firing refers to the combustion of biomass and coal for power production. Co-firing of biomass and coal can be advantageous with regard to substitution of fossil fuels, reducing fuel cost and emissions of NO_x and CO_2 minimizing waste and reduce soil and water pollution and increasing boiler efficiency. However, attention must be taken to increased deposit formation in the boiler and limitations in ash use due to constituents in biomass, especially alkali metals, which may disable the use of ash in building materials. Due to undesired changes of ash compositions, the share of biomass is usually limited to approximately 20% of the fuel input [105].

2.9.1. Biomass co-firing technologies

There are three general techniques comprise the co-firing technology: (1) Direct co-firing which involves blending the biomass and coal in the fuel handling system and feeding that blend to the boiler. (2) Parallel co-firing by which biomass is prepared separately from coal and injected into the boiler without impacting the conventional coal delivery system. (3) Indirect co-firing. In this technique biomass is gasified and then can be burned in either a boiler or a combined cycle combustion turbine generating plant. Most of the technical issues in combining biomass with coal for co-firing are related to fuel properties [10,59,60,98].

Direct co-firing is the least expensive, most straightforward, most commonly applied approach and the most commonly applied co-firing configuration as it enables co-firing percentages up to approx 3% on an energy basis, without significant investment costs. Indirect co-firing can offer a high degree of fuel flexibility, and the fuel gas can be cleaned prior to combustion to minimize the impact of the products of combustion of the fuel gas on the performance and integrity of the boiler. All of these options are shown in Fig. 17.

2.9.2. Technical and economic barriers to co-firing

There are some barriers to co-fire biomass with coal. These barriers include: biomass procurement practices to obtain low-cost fuels in a long term reliable manner; the impact co-firing on ash composition and ability to sell fly ash; the trade-off between the impact of biomass on emissions and fuel cost, relative to the impact

Table 19
Emissions factor from switch grass and coal [34].

Emission species	CO_2	N_2O	CH_4	SO_x	CO
Emission factor (g/kg Switch grass)	1525	0.09	0.14	0.10	4.12
Emission factors (g/kg coal)	2085	0.031	0.022	17.16	0.25

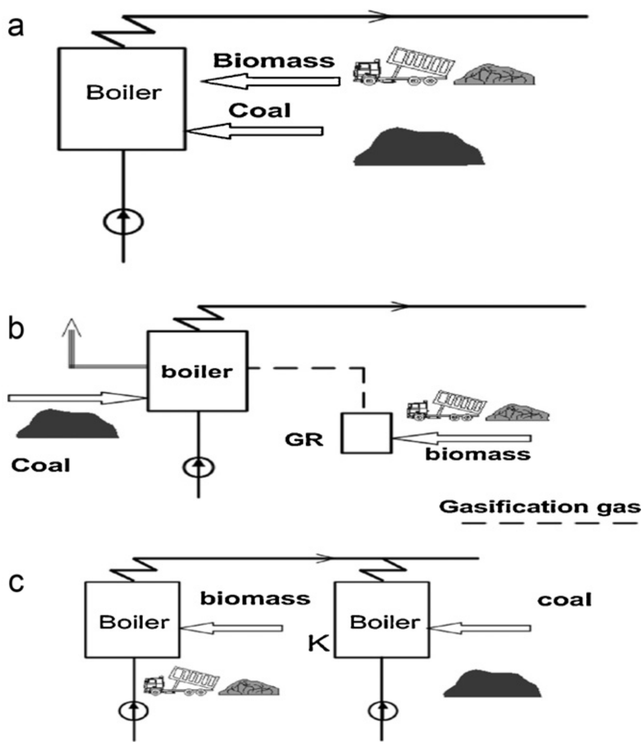


Fig. 17. Biomass co-firing technologies. (a) Direct co-firing. (b) Indirect co-firing. (c) Parallel co-firing [60]. Technical and economic barriers to co-firing.

Table 20
Emissions factor from electricity generation in the UK [23].

Fuel	Emission factor (g/kWh)		
	CO_2	SO_2	NO_x
Poultry litter	10	2.42	3.90
Forestry residues	24	0.06	0.57
Animal slurry	31	1.12	2.38
Natural gas	446	0.0	0.5
Coal	955	11.80	4.3

of biomass on boiler efficiency and plant net station heat rate in Btu/kWh [107].

2.10. The impacts of biomass

2.10.1. Emissions reduction of biomass

Environmentally, biomass is considered as an environmentally friendly fuel and has some advantages over fossil fuels such as coal, petroleum and natural gas (Tables 19 and 20 and Fig. 18). Biomass contains little sulfur and nitrogen (Table 13). Biomass co-combustion has significant positive SO_2 reductions of up to 75%. Moreover, most of nitrogen in biomass is converted to NH products such as ammonia NH_3 during combustion. Growing plants for use as biomass fuels may also help keep carbon dioxide levels balanced. Plants remove carbon dioxide as one of the greenhouse gases from the atmosphere when they grow. Moreover, thermal utilization of biomass can contribute to the reduction of CO_2 emissions since the same amount of CO_2 is extracted from the air during the growth period of the plants as it is released by combustion CO_2 balance. An evaluation of the CO_2 balance shows that, compared with the combustion of hard coal, the CO_2 emissions can be reduced by approximately 93%. The alkaline ash produced from biomass also captures some of the SO_2 and CO_2 produced during combustion.

Co-firing of biomass residues mitigates greenhouse gases by avoiding CH_4 release from the landfilled biomass. It is believed that CH_4 is 21 times more potent than CO_2 in terms of global warming impact. Co firing also reduces NO_x emission as great as 15% [19,62,94].

Stored biomass wastes anaerobically (in the presence of bacteria and moisture) release CH_4, NH_3, H_2S, amides, volatile organic acids, mercaptans, esters and other chemicals. By combusting the biomass, ambient emissions of these pollutants are reduced. For example, if cattle manure is used as an inexpensive alternative biomass fuel then many of the advantages described above are realized, in addition to avoiding contamination of soil, water and air due to otherwise stockpiled manure [19].

Cattle biomass (CB) has been proposed as a renewable, supplementary fuel for co-firing and reburning. Reburning coal with CB has the potential to reduce NO_x and Hg emissions from coal fired systems.

It is estimated that the net effect of wood fuel use in RWEDP member countries in 1994 implied a saving of about 278,000 kton of CO_2 which otherwise would have been emitted into the global atmosphere. Adverse environmental impacts of woodfuel use are due to unsustainable extraction from environmentally sensitive areas, which can lead to degradation of watershed and catchment areas, loss of biodiversity and habitat, etc. However, if the supply source is properly managed, woodfuel can contribute positively to the local and global environment. Woodfuel is CO_2 neutral, provided the rate of harvest equals the rate of re-growth. When wood and other biomass resources are properly valued by local populations their sustainable use contributes to the economical management of the local environment [16].

Biomass pyrolysis products as supplementary boiler fuels have been evaluated as supplementary fuels for reducing SO_2 and NO_x emissions from coal-fired boilers. The products produced by pyrolyzing biomass and then adding material to capture SO_2 (e.g. calcium-based sorbents) and reduce NO_x (ammonia-based compounds) [63].

In south East Asia, the environmental sustainability of oil palm biomass comes from when burning it to generate energy. Based on current typical industry practices for palm oil production, using palm oil for bio-fuel applications renders an average net CO_2 reduction of approximately 60%. In other words, the CO_2 emissions incurred in the palm oil supply chain are roughly 40% of the CO_2 emissions avoided by replacing fossil fuels [64]. This will alleviate a certain amount of carbon that otherwise would have been released to the environment by burning fossil fuels alone even if the biomass has to be transported from a distance far away. Another factor is that biomass is a waste product and can be utilized to reduce the country dependence on fossil fuel and ensure sustainable source of fuel, since biomass are renewable. Recently some studies have shown that oil palm plantations are more effective carbon sink (an area of dry mass that is capable to absorb harmful greenhouse gases such as carbon dioxide) comparing to rainforest. Oil palm plantation assimilates up to 64.5 ton of carbon dioxide per hectare per year while

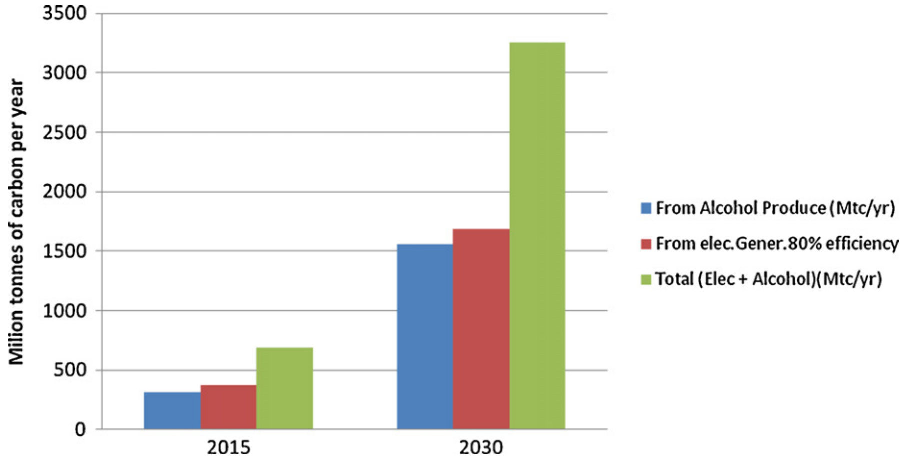


Fig. 18. World carbon abatement in 2015 and 2030 due use of sugarcane biomass [61].

virgin rainforest only can assimilate 42.2 ton per hectare per year [65].

Bananas give the advantage of producing a very clean form of biogas, consisting of just methane and carbon dioxide as compared to the other waste streams such as human sewage, piggery or feedlot waste, with the added attraction of less noxious odours as well as different trace elements [18].

A number of major utilities are evaluating co-firing of biomass in existing coal fired power stations. Benefits of co-firing include the reduction in CO_2 emissions from the combustion of fossil fuels, the reduction of SO_2 formation through a decrease in fuel bound sulfur and the reduction of NO_x formation through a reduction in fuel. Incentives which exist for utilities include site specific cases where the biomass purchase price is less than that of coal, indirect benefits to the forestry and secondary wood products industry by providing new markets for wastes and residues, as well as dedicated feedstocks, thereby promoting economic stability in the utilities service area; and the potential to develop feedstock infrastructure and jobs for long term biomass development and use [31].

According to Abdelaziz [66] when switching between biomass and diesel in the industrial boilers the results show that the total emission reduction of CO_2 when switching in different percentage between biomass and diesel are about 4778 ton in case of 80% diesel and 20% biomass consumption, 9557 ton in case of 60% diesel and 40% biomass and 11,946 ton in case of 50% diesel and 50% biomass consumption (Fig. 19).

2.10.2. Environmental effects of biomass:

Most of the biomass wastes/fuels such as MNSW and landfill gas contain chlorine, creating heavy metals and organic compounds such as dioxins (the most toxic chemicals known to science) when burned and may cause many health problems.

Waste incineration is the worst category of biomass. What makes waste dangerous is not its volume, but its toxicity. Toxic constituents of wastes can cause all sorts of health and environmental problems. When wastes are incinerated, their toxic constituents are liberated into breathable air emissions and the toxic ash contaminates groundwater. The ash that is left then has a higher surface area and is more dangerous in a landfill, where rainwater will leach out the toxins more readily than if the waste is left unburned. Incinerator ash has been promoted for such applications as ingredients in cement, fill for reclaiming mines, fertilizer, biochar (charcoal), industrial tile and road base. These are more dangerous than landfilling, bringing contamination closer to where they can harm people. Incineration has become a dirty word since activists have stopped hundreds of incinerators since the 1980s. Newer types (gasification, plasma arc and pyrolysis) claim not to be incinerators, but share the same fundamental problems [23,67,96,109].

Thy [93] shows that combustion of biomass at temperatures of at least 575 °C results in complete volatilization of mercury leaving solid ash and slag residuals with mercury contents at or near the lower limit of detection (5 ppb). The mercury strongly concentrated in fly ash can reach concentrations up to 40 times the corresponding fuel concentrations.

Other Environmental effects of biomass [68,69,103,104]:

i. Biomass energy may be 'carbon neutral' but it is not 'nutrient neutral'
ii. Land and water resources
iii. Soil erosion and water run-off
iv. Nutrient removal and losses
v. Loss of natural biota, habitats and wildlife.
vi. Deforestation and forest degradation
vii. Loss of biodiversity and land degradation

2.11. Economic and social impacts of biomass

Even though environmental policy may provide the main incentive for initiating a coal and biomass cofiring projects, most projects require favorable economics to continue operation [31,97,101].

There are many different types of biomass that can be grown for the purpose of producing energy. Crops, for example, have been used for energy. However, there are two main factors, which determine whether a crop is suitable for energy use. The first one is the high yield of dry material per unit of land (dry tons/hectare). A high yield reduces land requirements and lowers the cost of producing energy from biomass. Secondly, the amount of energy, which can be produced from a biomass crop, must be less than the amount of energy required to grow the crop. Generally, the cost of producing energy from fossil fuels exceeds the cost of biomass fuels. Biomass not only has considerable potential as a fuel source, it also shows a reasonable cost level in comparison to other renewable energies [14,97].

The application of biomass offers many economical advantages like: conservation of fossil fuel resources, reduction of the dependence on fuel imports, utilization of agricultural and forest residues, reduction of emission of harmful species from fossil fuel combustion, recultivation of non-utilized farming areas, and minimization of waste disposal [70,71,97].

If biomass has to be transported long distances, it can become more expensive than coal that is fired in the boiler. Because of these economics, co firing at some electric utilities is unfeasible. The size

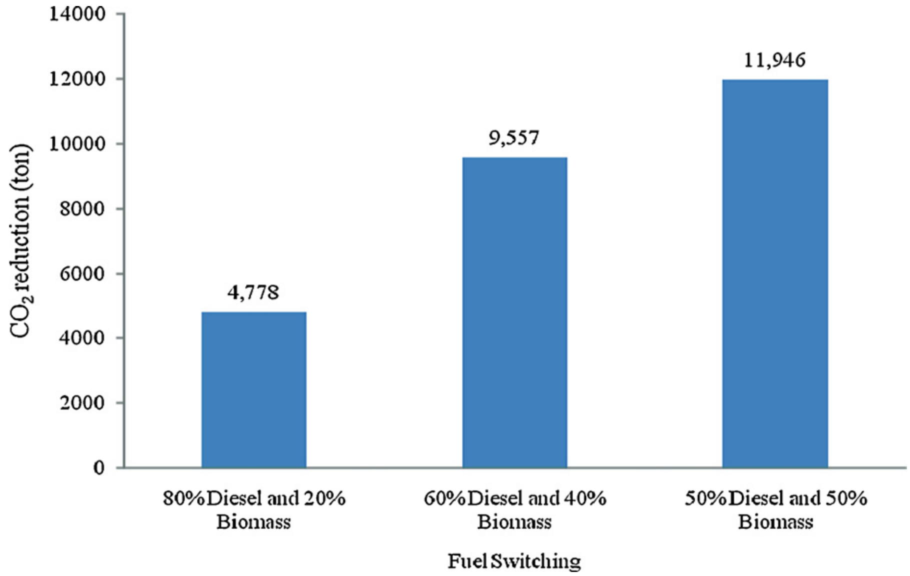


Fig. 19. Total CO_2 reduction (ton) when switching between biomass and diesel [66].

of the unit may permit the usage of biomass due to its location within a reasonable transportation distance along with the cost of the current boiler fuel, thus allowing more to be spent on obtaining and transporting the biomass.

The economic evaluation of cofiring coal with biomass in boilers is complex. The evaluation must include several components. The price of the biomass fuel is frequently a very important, if not the most important, determinant of a plants economic viability, particularly if high percentages of biomass fuel are used. Biomass fuel prices can be either positive or negative within an extremely broad price range. Operating and maintenance costs are dependent on the technology used to store, process and burn the fuels and the potential impact of fuel characteristics on plant performance, including efficiency. The latter cost projection can be complicated by the variable nature of some waste fuels [31,97]. Wood fuel supply implies labour for growing, harvesting, processing, wholesaling, transporting and retailing the product. Woodfuel business is the main source of income for about 10% of rural households, and for about 40% of their cash earnings. In times of hardship, or when harvests are insufficient for subsistence, the opportunity to generate income in woodfuel business provides a safety-net for poor persons, many of whom are women. On the demand side, wood fuels are a basic commodity serving the daily needs of some 2 billion people in RWEDP member-countries. However, access to the fuels is much skewed. In areas or times of scarcity, landless and unemployed people and low-wage earners suffer from high prices or the non-availability of wood fuels [109].

Prices of woodfuels vary, depending on markets. Part of the market is still not monetized (in most places some 70%). Commercial markets are generally found in cities and towns, but also in villages, where fuelwood is traded. Local prices are largely determined by opportunity costs of labour and resource availability, which generally does not reflect the real economic (including environmental) costs. A typical price in RWEDP member-countries is 40 US$ per ton. Stumpage fees can be anything between 0% and 20% of retail prices [16].

In Malaysia, utilization of oil palm biomass could also ensure social sustainability by creating new employment opportunities in rural areas in the developing country like Malaysia. This is because labour requirement for biomass energy is relatively high, especially in the cultivation of energy crops [65].

Table 21
Life cycle comparison of biomass and natural gas boiler [72].

	Biomass boiler	Natural gas boiler
Capital expense ($)	3,942,664	850,000
Principle and interest ($)	4,779,617	1,050,061
Operating costs ($)	508,291	310,001
Measurement and verification costs ($)	256,974	
Total cost ($)	5,544,882	1,360,062
Energy saving ($)	23,032,372	No operating or energy saving
Net saving ($)	17,487,490	

According to Daskalakis and Iyer [72], a cost analysis was conducted for Arnot Ogden Medical Centre, a non-for-profit, 433,000-sqft medical facility in Elmira, N.Y to replace boiler 3 which is the oldest and least efficient boiler. The wood gasifier proved economically superior to the fossil-fuel alternative. Although the installation of fossil-fuel-fired equipment would have been less expensive, the wood-gasifying boiler offered a net benefit of nearly $19 million in operational and capital-investment savings over a 20-year life cycle (Table 21).

In Malawi, a case study has demonstrated that in the energy sector, woodfuel is the most important employer and cash earner being worth US$ 49 million in 1996 and US$ 81 million in 2008. In 1996 an estimated 93,500 full-time people (upwards of 135,000 part-time people) were gainfully employed in growing, producing, transporting and trading wood energy, many being rurally based. In 2008 an estimated 133,000 full-time people were employed in the ‘commercial’ wood fuel business. By contrast, the so called commercial energy (coal, petroleum products and electricity) provided employment to about 3400 full-time people in 1996 and 4600 in 2008, most of whom are urban based [73].

According to Abdelaziz [66], when switching between biomass and diesel in the industrial boiler the results show that the total annual bill saving when switching in different percentage between biomass and diesel in the Malaysian industrial boilers are about RM 799,278 in case of 80% diesel and 20% biomass consumption, RM 1,447,761 In case of 60% diesel and 40% biomass consumption and RM 1,872,532 in case of 50% diesel and 50% biomass consumption respectively (Fig. 20).

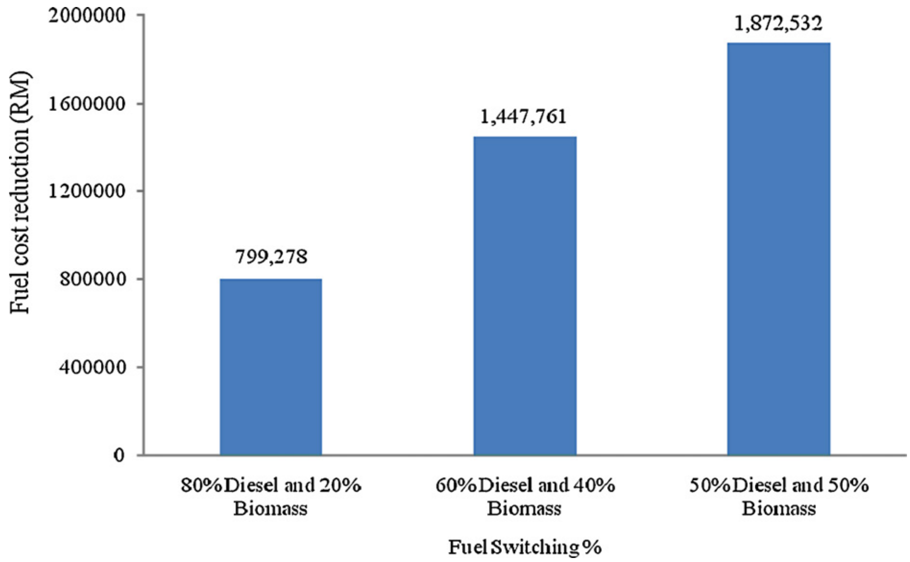


Fig. 20. Total fuel cost reduction (RM/year) when switching between biomass and diesel [66].

The major social impacts of biomass will be an increase in employment rate. However, it can also increase the occupational health and safety problems. Total employment overall is expected to increase if the nation's energy needs are provided by biomass resources. The labour force would be needed in agricultural and forest production to cut, harvest, and transport biomass resources and in the operation of conversion facilities. The direct labour inputs for wood biomass resources are 2–3 times greater per million kcal than coal. A wood-fired steam plant requires, 4 times more construction workers and 3–7 times more plant maintenance and operation workers than a coal-fired plant. Including the labour required to produce corn, about 18 times more labour is required to produce a million kcal of ethanol than an equivalent amount of gasoline [74].

2.12. Transportation of biomass

Transportation is a cost element in any energy project, and this is especially true for biomass because of the lower energy density compared with fossil fuels. Transportation costs for biomass and its products have a distance fixed component (DFC) that is incurred regardless of the distance traveled, and a distance variable component (DVC) that is directly related to the distance traveled. Both factors must be included in an analysis of transportation costs.

There are four modes of biomass transportation [75]:

1. Truck transport
2. Truck plus rail transport.
3. Truck plus pipeline transport.
4. Truck plus ship transport

Many field sources of biomass are, by their nature, remote from the population centers that will use the produced energy. Thus, developers of such biomass projects will have the alternative of moving the biomass to a plant near the energy consumer, or moving the produced energy from a remote biomass processing plant.

There are two issues arise with transportation of biomass: achieving lowest possible cost and avoiding road and community congestion during delivery. Train transport has promise in each of these areas. [76].

2.13. Densification of biomass:

Densification of biomass is a very important factor to increase its density and thus improve biomass quality. Densification has the following advantages:Densification raises the energy density (kJ/m^3 Fuel) which makes combustion in boilers more efficient.Densification reduces costs associated with the handling, storage and transportation of the biomass fuel.Densification improves biomass stability and durability

Densification of biomass can be categorized into 5 types: (1) Baling, (2) Extrusion, (3) Pelletizing, (4) Briquetting roller press, and (5) Punch and die press.

2.13.1. Balers

Baler uses ram mechanism to compress biomass in a specifically designed steel chamber, then the compressed biomass is banded or tied prior to being released and hauled away in a uniform size and shape. Commonly, balers are used to reduce storage space and transportation cost.

2.13.2. Extrusion

Extrusion can be defined as shaping by forcing a material through a die. Fundamentally the process of extrusion consists of converting a suitable raw material into a product of specific cross sectional shape by forcing the material through a dire or orifice under controlled conditions. There are various types of extrusion such as:

2.13.2.1. Ram-type extrusion. This type uses a reciprocating ram (piston or rod) that forces raw material falling from the feed hopper through a tapered die. The materials are pushed by the reciprocating piston against the die paper. It makes use of wall friction and contraction of the die cross sectional-area, causing resistance to the flow of materials through the die.

2.13.2.2. Screw extrusion. This type uses a screw to force a feedstock under high pressure into a die, thereby forming large cylinder s 2.5–10 cm in diameter. There are three types of screw presses: (a) the conical screw press, (b) the screw press with a heated die, and (c) the twin -screw press.

2.13.2.3. PelletingS (pelletizing). The pelletting press consists of a drum-shaped hard steel die which is perforated in the perimeter

with a dense array of holes 0.3–1.3 cm in diameter. The die rotates against an inner pressure roller, forcing the biomass feedstock into the die holes at pressure of 10,000 psi as the pellets are extruded through the die holes, they broke off at a specified length (normally less than 3 cm). There are three types of pellettizers: (a) ring-die type, (b) disk-die type, and (c) cuber type.

2.13.3. Briquetting roll press

Briquetting refers to the compacting into lumps of crushed materials. The products are normally pillow shape and relatively large in size (1 in. or larger). In this type precompressed feedstock falls in between two rollers rotating in opposite directions. The feedstock is compacted into pillow-shaped briquettes.

2.13.4. Punch and die

Punch and die press uses two opposing pistons inside a cylinder to compress the material in the mold. Once compressed, the product in the form of a slug, log or tablet is pushed out of the mold by one of the two pistons. Due to this method, the material can compacted under very high pressure even when the material is relatively wet.

2.13.5. Variables influencing biomass densification

The following factors were found to influence densification of biomass [77]:

1. Process variables: (a)Temperature, (b) pressure and pressure application rate (compression velocity), (c) hold time, and (d) die geometry.
2. Feedstock/material variables: (a) Moisture content, (b) particle size, shape, and distribution, (c) biochemical characteristics, and (d) pretreatment

2.14. Problems and remedies of biomass

2.14.1. Fouling, deposits, slagging and corrosion issues

Fouling or deposits are commonly known as the layers of materials (ash) collected on the surface of heat transfer equipment. Slagging characterizes deposits on the furnace walls or other surfaces exposed to predominantly radiant heat. Corrosion is the deterioration of intrinsic properties of a material due to reaction with its environment. Corrosion can be caused either directly by gas phase species, by deposits or by a combination of both. In boilers, these problems are regarded as a major issue that can affect the design, life time and operation of combustion equipment, increase the operating cost, decrease boiler efficiency, increase carbon dioxide emissions, deteriorate combustion behavior with higher combustion temperatures, increase nitrogen oxides and carbon monoxide, reduce heat transfer and causes corrosion and erosion (Fig. 21). The main contributions to fouling, deposit formation, slagging and corrosion come from Ash composition together with sulfur and chlorine contents which facilitates the mobility of many inorganic compounds, in particular alkali compounds including Potassium and Sodium form alkali silicates that melt at low temperatures (can be lower than 700 °C), thus providing a sticky surface for enhanced deposition. Inorganic is less well understood than that of organic materials. Because biomass fuels contain a larger variety of inorganic materials compared to coal, issues of fouling and corrosion need to be explored. This is particularly true for some agricultural residues and new tree growth where the ash can have relatively high alkaline metal contents, particularly sodium and potassium. Sodium and potassium lower the melting point of ash and, hence can increase ash deposition and fouling of boiler tube [4,14,19,78–80].

The corrosion mechanisms in biomass fired boilers can be broadly classified into three classes: (1) Corrosion associated with gas species (active oxidation). (2) Solid phase corrosion. (3) Molten phase corrosion. A general sketch of potassium, sulfur, and chlorine chemistry in a biomass fired boiler is given in Fig. 22 [4,81].



Fig. 21. Photograph of deposit forming from wheat straw on a simulated boiler tube [81].

The removal of these elements has been tested by leaching biomass fuel with water. In general, leaching reduces the volatilizion of inorganic species at ashing temperature higher than 575 °C. Leaching leads to a notable decline in the alkali index which leads to reduce fouling [82].

Another way to remove the effect of Cl in deposits and subsequently corrosion is basically focused on the capture of alkali compounds. Studies suggest the use of different materials such as bauxite, kaolinite, limestone and magnesium oxide and other additives to produce high melting point alkali compounds relative to alkali chlorides. These additives are meant to increase the melting point of the ash formed during combustion. With the use of most of these materials, Cl is released in gas phase, thus not totally eliminating the corrosion effect [4,83].

The application of a hybrid system that combine Neural Networks (NNs) and Fuzzy-Logic Expert Systems (FLES) has been selected as a proper solution in biomass-fired boilers. This Hybrid System uses several sets of NN with different objectives: boiler monitoring, fouling forecasting, prediction of boiler behavior and the cleaning effect if a sootblowing cycle was activated. The application is completed by the development of a FLES that takes the sootblowing decision. Validation shows important energy saving of 3.5% between Hybrid System outputs and real data obtained from a biomass boiler. This system is shown in Fig. 23 [80,84].

2.14.2. Agglomeration

Agglomeration can occur as a result of two phenomena: (i) accumulation of low-temperature-melting salts of potassium and phosphorous, and (ii) in the presence of silica from sand and calcium from fuel, potassium phosphate can react with silica forming low-temperature-melting silicates of potassium and calcium while phosphorous bounds with calcium. Agglomeration is responsible for causing defluidization in boilers [4].

In BFBs, the main reason of agglomeration problems comes from the second phenomenon. In its extreme case, agglomeration leads to unscheduled shutdown of the plant. For these reasons, it is essen-

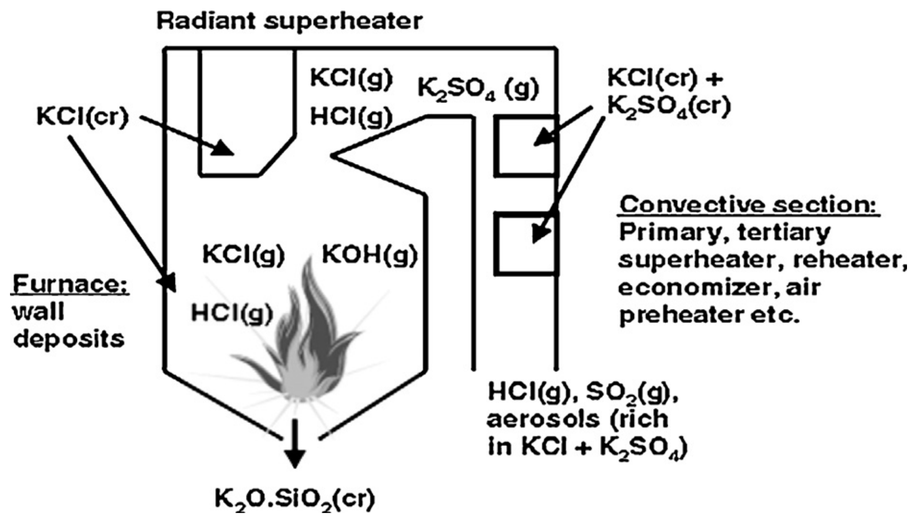


Fig. 22. Principal pathways of potassium, sulfur and chlorine in a biomass fired boiler [4].

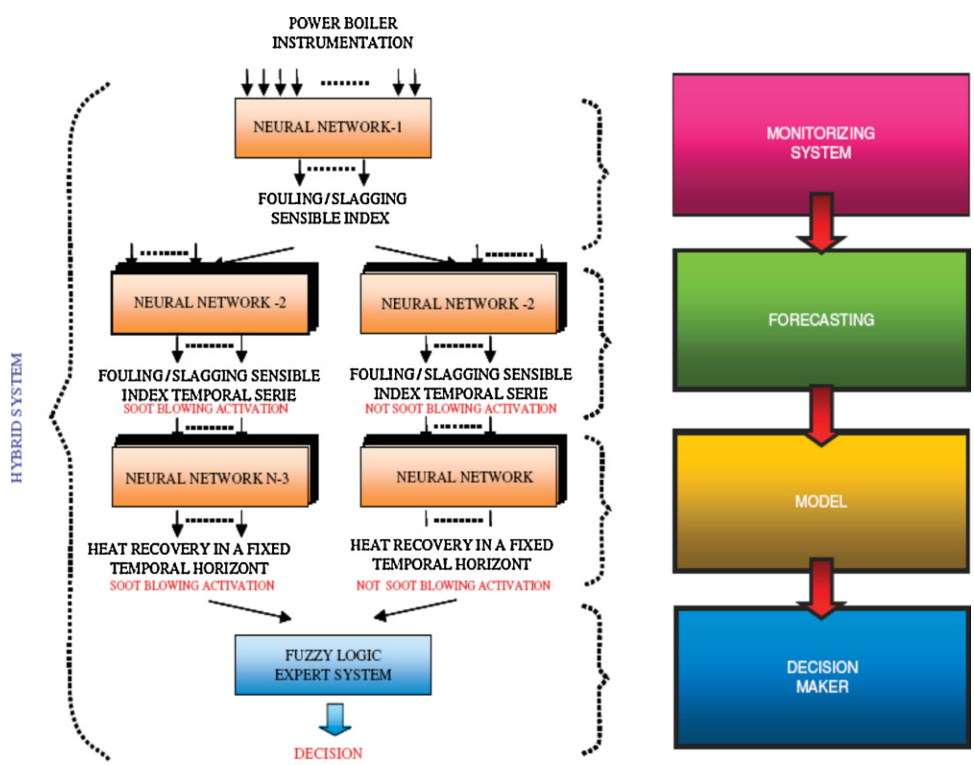


Fig. 23. Biomass boiler control system design [80].

tial that this problem should be brought under control if not totally eliminated.

There are at least three different mechanisms identified for ash sintering:

- The presence of a liquid phase
- Solid-state sintering
- Chemical reactions.

In biomass fired FBC boilers, partial melting is considered as the main mechanism leading to bed agglomeration. Fig. 24 shows the development of an ash layer rich in potassium after few hours of operation in a fluidized bed boiler which ultimately results in the formation of agglomerates.

There are number of measures to deal with this phenomenon: Co-combustion with clean fuels generally delays the time of occurrence for agglomeration and it also has a very limited window of operation.

Different additives including kaolin, dolomite limestone, lime, alumina etc. are other solutions that can reduce agglomeration and slagging by coating sand particles, thus preventing reactions between silica and potassium phosphate. However, efficiency, subsequent problems, and applicability of such materials have definitely limited their use.

The third most attractive remedy to agglomeration is the use of alternative bed material due to its ease of use and low costs. Different alternative bed materials including dolomite, magnesite, ferric oxide, alumina, feldspar, and aluminum rich minerals have been proposed and tested with a range of problems. Problems associated

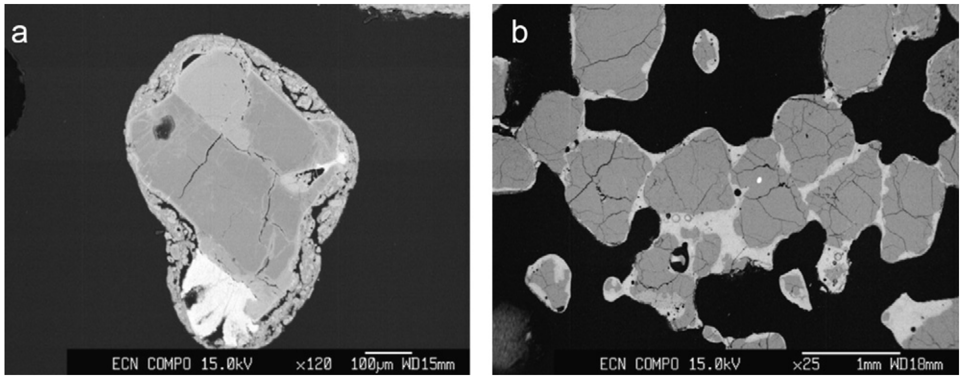


Fig. 24. (a) Layer built up of ash rich in potassium around a sand particle. (b) Agglomerate formation-binding material rich in potassium [4].

with the proposed materials include high attrition and entrainment rates, chemical stability, and other problems (namely windbox and air nozzle plugging).

Recently, a new patented bed material called "Agglostop" has been reported to be successfully used in a number of plants without any operational problems [4,85].

2.14.3. Trace metal emissions

Trace elements (As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb,V, Zn) present in some biomass fuels play a great environmental concern for heavy metal emissions. Cd in agricultural products is potentially a public health problem, owing to its accumulation in the kidneys and its effects on skeletal density.

The presence of the trace elements in the fuel depends upon the source of biomass. For example, for agricultural biomass, age of plant, growing site, distance from the source of pollution generally determine the trace element fraction in the fuel while for others, past processing of the source is relevant (e.g. demolition wood).

There are some suggested measures to prevent the presence of some of these harmful metals. For instance, adsorption and chemical reaction by adsorbent materials such as alumina, kaolinite, bauxite, and emathlite can capture these heavy metals. Another way, absorption and chemical reactions of the heavy metals cadmium and lead with absorbent particles such as activated carbon or other appropriate sorbents, post-precipitation, ion exchange, etc. is also applied in order to remove these toxic metals. The disposal of the metal concentrated ash to a landfill is another effective measure [4].

2.14.4. Low heating value

Moisture in the fuel reduces the heating value compared to a dry weight determination. Because of the low heating values, biomass is accompanied by flame stability problems. It is anticipated that blending biomass with higher quality coal will reduce the flame stability problems. One of the possible solutions for this problem is co-firing with coal. It has been found that 20% biomass mix with coal can contribute to huge benefits in boilers [14,42].

2.14.5. Marketing problems

There are also various obstacles to market penetration and strong competition from fossil fuels and electricity. For example, wood chips or pellets cannot fuel a gas or oil burner. To switch from an electricity or fossil fuel-driven heating system to biomass you need a new burner. This requires a lot of capital and in many countries the economic incentives to switch are too weak. Thus, global and regional supported policies and incentives are vital to boost utilization of biomass in boilers [11].

2.14.6. Storage problem

Storage of biomass is a very vital link on the supply chain stages. Most relevant researches chose low cost storage option such as on-field storage. The technique of on-field storage causes significant losses of biomass material. Moreover, moisture cannot be controlled and reduced to a desired level. This will lead to many potential problems in boilers such as self ignition. This method is also responsible for many health and safety problems, such as spores and fungus formation. Finally, the farmers may not allow on-farm storage of the biomass for a significant time period, as they may want to prepare the land for the next crop.

Intermediate storage locations between the fields and the power plant have been suggested to sort out the above mentioned problems. The fuel has to be transported twice by road transport vehicles (first from farm/forest to the intermediate storage facility and then from storage to the power station). However, this fact will result in a higher delivered cost than a system in which there is only one road transport movement (directly from farm/forest to power station). Using an intermediate storage stage may add in the region of 10–20% to the delivered costs, as a result of the additional transportation and handling costs incurred.

Settling the storage facility next to the biomass power plant is the best way to deal with this problem. This concept aims at reducing faster the biomass moisture content and prevents material decomposition as well as fungus and spores formation. Using storage facilities attached to the power plant is the only viable case of accelerating the drying process of the biomass, as dumped heat may be used without need for extra energy consumption. In addition to, this concept will also overcome the high transportation cost mentioned in the intermediate storage locations [86].

2.14.7. Barriers for biomass production in South East Asia

2.14.7.1. Technical barrier. There are no local manufacturers or agents of equipment for the efficient conversion of various types of biomass to energy. Related to this is the absence of a network for the general maintenance as well as technical maintenance of these equipments.

2.14.7.2. Financial barrier. The main financial barriers to biomass production for energy are the high-energy production cost, unavailability of subsidies for energy production from renewable energy sources, and the energy pricing which excludes the external costs of energy use. The front end costs for the newer technologies are comparatively higher and there are insufficient incentives for the use of these technologies. There is also a perceived financial risk which results in a lack of appropriate finances/credit mechanisms.

2.14.7.3. Policy and institutional barriers. There is no national strategy or priority given to biomass for energy use. The fact that there

Table 22
Status of SREP projects approved by SCORE as at 2005 [88].

Type	Energy resource	Approved application	Generation capacity	Grid connected capacity (MW)
Biomass	Empty fruit bunches	25	220.5	174.8
	Wood residues	1	6.6	6.6
	Rice husk	2	12.0	12.0
	Municipal solid waste	1	5.0	5.0
	Mix fuels	3	19.2	19.2
Landfill gas		5	10.2	10.0
Mini-hydro		26	101.9	97.4
Wind and solar		–	–	–
Total		63	375.4	325.0

are no local expertise for renewable energy project feasibility study and design is a barrier to the dissemination of information and in providing awareness on renewable energy production technologies. The result is lack of coordination among different national agencies and lack of a designated agency responsible for undertaking renewable energy programs [1].

2.14.8. Biomass conversion challenges in USA

In the U.S., shifting power generating capacity to biomass will not be easy. Biomass as a fuel source for large-scale power generation is in its infancy. Suppliers and supply chains have not yet been developed on the scale necessary to supply volume of biomass necessary to meet U.S. power needs. Unlike the coal supply chain that has been in place for many years, it is not clear at present how the biomass supply chain will or should develop. This is made more complex as numerous utilities are considering entering the biomass market before it is well understood how the competition for fuels sources could evolve. Key questions for a utility considering a conversion to biomass are likely to include the following [87]:

- Type of biomass: Wood vs. agricultural products, raw vs. pelletized, purpose grown vs. byproduct/residual; torrefaction; specifications (Btu content, moisture content, size, emissions)
- Sourcing: Biomass origins, suppliers, producer facility sizes, pellet plant locations (if applicable)
- Transportation: Modal options, equipment requirements, unloading infrastructure, delivery quantities
- Storage/Handling: Type of fuel storage (indoor for certain types of biomass pellets), conveying infrastructure, dust control systems, fire suppression systems
- Boiler: Type of boiler to use or boiler conversion options.

2.15. Policies of biomass

2.15.1. Policies of biomass in Malaysia

Since 1999, Malaysia has adopted the five-fuel diversification strategy energy mix, whereby the five main sources are oil, natural gas, coal, hydro and renewable energy. Biomass fuels hold great promise to be used in different industrial applications as an abundant resource in Malaysia. However, RE in Malaysia is still being generated on a small-scale basis only. Biomass has been suggested as a component of Clean Development Mechanism (CDM). The Biomass Energy Plant Lumut is the first Malaysian project to be registered at the UNFCCC as a CDM project. In is this project biomass has been co-fired with coal in some industries. The Small Renewable Energy Power (SREP) Program was launched in 2001 and initially covered biomass, biogas, landfill waste and mini-hydro. Latest report from Malaysia Energy Centre (PTM – Pusat Tenaga Malaysia) shows 60 projects have been approved as in 2005, using various types of renewable energies. Among all the sources of RE, biomass appears to be the most promising, especially from empty fruit bunches since Malaysia is one of the world's top producers of oil palm (Table 22) [88].

2.15.2. Policies of biomass in India

India has been implementing one of the largest renewable energy programs in the world. The Prime Minister of India has announced a goal of 10% share for RE in the power generation capacity to be added during the period up to 2012. For this concern, renewable energy technologies (RETs) programs were initiated in late 1970s. In 1981 the Government of India established a Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology to promote research and development in the field of renewable energy. In 1982 CASE was incorporated in the Department of Non-conventional Energy Sources (DNES) and in 1992 DNES became the Ministry for Non-conventional Energy Sources (MNES). Biomass is potentially the most suitable renewable energy resource to alleviate concerns raised by the energy crisis because it has a large diverse portfolio including efficient biomass stoves, biogas, biomass combustion and gasification and process heat and liquid fuels.

India has also formulated and implemented a number of innovative policies and programs to promote bio-energy technologies. In industrial sector, biomass resources such as crop residues and agro-industrial wastes for generation of energy has been suggested for meeting total/partial requirements for both electrical and thermal energy as shown in Table 23 [89].

Biomass Policies under the Ninth Plan (April 1997 to March 2002) aim at expanded and ambitious biomass program. It is proposed to establish an international centre for biomass production and conversion technologies. The major biomass proposals include gasifier demonstration program for higher capacity (100 kW) systems, fiscal and financial incentives for biomass briquetting with a view to enhance supply of briquettes to replace coal and oil in industrial sector, and an electrification pilot project by MNES through biomass gasifiers and biogas. Under this policy, biomass electricity penetration can reach 35 GW in 2035 (9% of India's electricity generation) compared to 10 GW in 2010 [90,91].

2.15.3. Policies of biomass in USA

Europe is several years ahead of the U.S. in biomass development. However, state-level renewable portfolio standards are now mandating that U.S. utilities begin the process of embracing biomass. Moreover, there are a variety of federal and state policies supporting and guiding the development and use of biomass. These policies include biomass research funding; encourage the use of biomass and fiscal policies. Most of these policies are directed towards reducing dependence on foreign sources of oil, thereby increasing diversity and security of the nation's energy portfolio. It is possible that within several years, the U.S. biomass landscape may more closely resemble that of Europe.

The U.S. Energy Information Administration (EIA) expects biomass consumption for power generation to increase significantly in the coming future. It is anticipated that biomass

Table 23
innovative policies for utilizing biomass resources in the Indian industrial sector [89].

Land category	Sub category	Area (Mha)	Biomass resource with energy potential	Potential energy end-use	Physical quantity (MT Year^{-1})	Energy potential
Crops	Rice	46.1	Straw + husk	Gasification for power	41	4700 MW
	Maize	6.6	Stalk + cobs		6.2	700 MW
	Cotton and others	16.8	Stalk, coconut shells, fronds	Cogeneration for power	240	28,000 MW
	Sugarcane	5.5	Bagasse + leaves	Gasification for power	163.5	8900 MW
Crop land	Marginal crop land	14	Woody biomass		84	9700 MW
Waste land	High potential	28.5			171	20,000 MW
MSW			Combustible organic matter	Biomethanation for power	56	6500 MW
Forest	Jatropha curcas	65	1.50 MT of oil seeds	Bio diesel for transportation fuel	3.23	34.11 PJ
	Rice Bran		0.47 MT of oil seeds			
	Neem		0.40 MT of oil seeds			
	Sal		0.72 MT of oil seeds			
	Karanja		0.14 MT of oil seeds			
Crop land	Marginal crop land	13.4	Oil from Jatropha curcas	Bio diesel for transportation fuel	16.08	530.6 PJ
Waste land	Marginal potential	9.4		Bio diesel for transportation fuel	11.28	372.24 PJ
Crops	Sugarcane	5.5	Ethanol	Transportation fuel	20.9	562.2 PJ
Dung	Cattle		Dung	Biogas for cooking	344	336 PJ
	Buffalo				315	

consumption will increase from 60 billion kWh in 2008 to 188 billion kWh by 2020, of which 165 billion kWh is to come from wood and other biomass [87,92].

2.16. Future of biomass

Future demand of biomass has to be satisfied in a sustainable way. For example, if wood fuel is extracted from environmentally sensitive areas, it can lead to degradation of watershed and catchment areas and loss of biodiversity, habitat, etc. Thus, there is a need to produce biomass in sustainable way such as energy plantations on deforested land and surplus land taking into account the future land requirement for food production [1].

The future of biomass heating depends upon the development of the markets for fossil fuels and on policy decisions regarding the heating market. *AEBIOM* believes the principle of efficiency should guide future biomass strategy. The main goal should be to maximize the contribution of biomass to total energy consumption at low costs to the consumer. Making this happen requires at least three things: Minimization of the conversion losses; keeping final energy yields per hectare as high as possible; Low costs to improve the competitiveness of the European economy. Based on the criteria of high conversion efficiency, high final energy output per unit land and low cost, the priorities for the future biomass deployment are bio heat followed by transportation fuels and electricity from heat-driven cogeneration units [11].

3. Conclusion

Biomass is a carbon neutral source of energy because when fully combusted the amount of carbon dioxide produced is equal to the amount which was taken from the atmosphere during the growing stage. Therefore, biomass is regarded as renewable energy resource and can play an important role in the future fuel supply trends. Biomass is a very promising source of energy in boilers. In this review, several aspects of biomass have been investigated such as conversion efficiencies of biomass, compositions of biomass, estimating the higher heating value of biomass, comparison between biomass and other fuels, combustion of biomass, co-firing of biomass and coal, impacts of biomass, economic and social analysis of biomass, transportation of biomass, densification of biomass, problems of biomass and future of biomass.

In this paper, it has been found that using biomass in boilers offers many advantages such as Mitigation of hazardous emissions such as CO_2, NO_x, CH_4, SO_x and CO, diversification of fuel supply and energy security, Potential use of oceans and low-quality soils, and restoration of degraded lands, economical, social and environmental benefits such as financial net saving, conservation of fossil fuel resources and job opportunities creation. However, care should be taken to other environmental impacts of biomass such as land and water resources, soil erosion, loss of biodiversity and deforestation. Fouling, Agglomeration, Trace metal emissions, marketing, low heating value, storage and collections and handling problem are all associated problems when burning biomass in boilers.

Biomass contains varying amounts of chemical and phase compositions. These compositions are a unique fundamental code that characterizes and determines the properties, quality, potential applications and environmental problems related to any fuel and may also help in understanding the combustion phenomenon of biomass beside estimating the higher heating value of different types of biomass. In this review different analysis of biomass have been included such as structural analysis, proximate analysis, ultimate analysis and ash analysis. All these analysis have been illustrated in comprehensive tables.

Biomass can be converted to fuel by means of numerous processes. The actual choice of a process will depend on the type and quantity of available biomass feedstock, the desired energy carrier(s) (end-use), environmental standards, economic conditions and other factors. Some of these processes include direct combustion, prylosis, fermentation, gasification, anaerobic digestion and chemical conversion.

Biomass differs from coal in many important ways, including the organic, inorganic and energy content and physical properties. These differences might affect replacing coal by biomass and also affect co-firing of biomass and coal boilers. Thus, further studies are needed to be conducted such as improvement in boilers design, materials and combustion technology.

There are many combustion technologies available for biomass combustion such as: fixed bed combustion, fluidized bed combustion and pulverized bed combustion. However, it has been found that fluidized bed combustion is the best technology used to burn a fuel such as biomass with low quality, high ash content and low calorific value.

The future of biomass in boilers depends upon the development of the markets for fossil fuels and on policy decisions regarding the heating market. There are some policies that already implemented in some countries around the world such as in Malaysia, India and USA. All these policies promoted using biomass in different sectors by setting some standards, fiscal policies, taxes and funding.

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